on Theory of Neutrino mass and mixing

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CNNP Catania, October 20 , 2017

R. Davis in 80ies: “Models of neutrino masses are so numerous that they can compose the Dark Matter in the Universe”

This can not be true: with present number of models the Universe would be overclosed many times contradicting observations

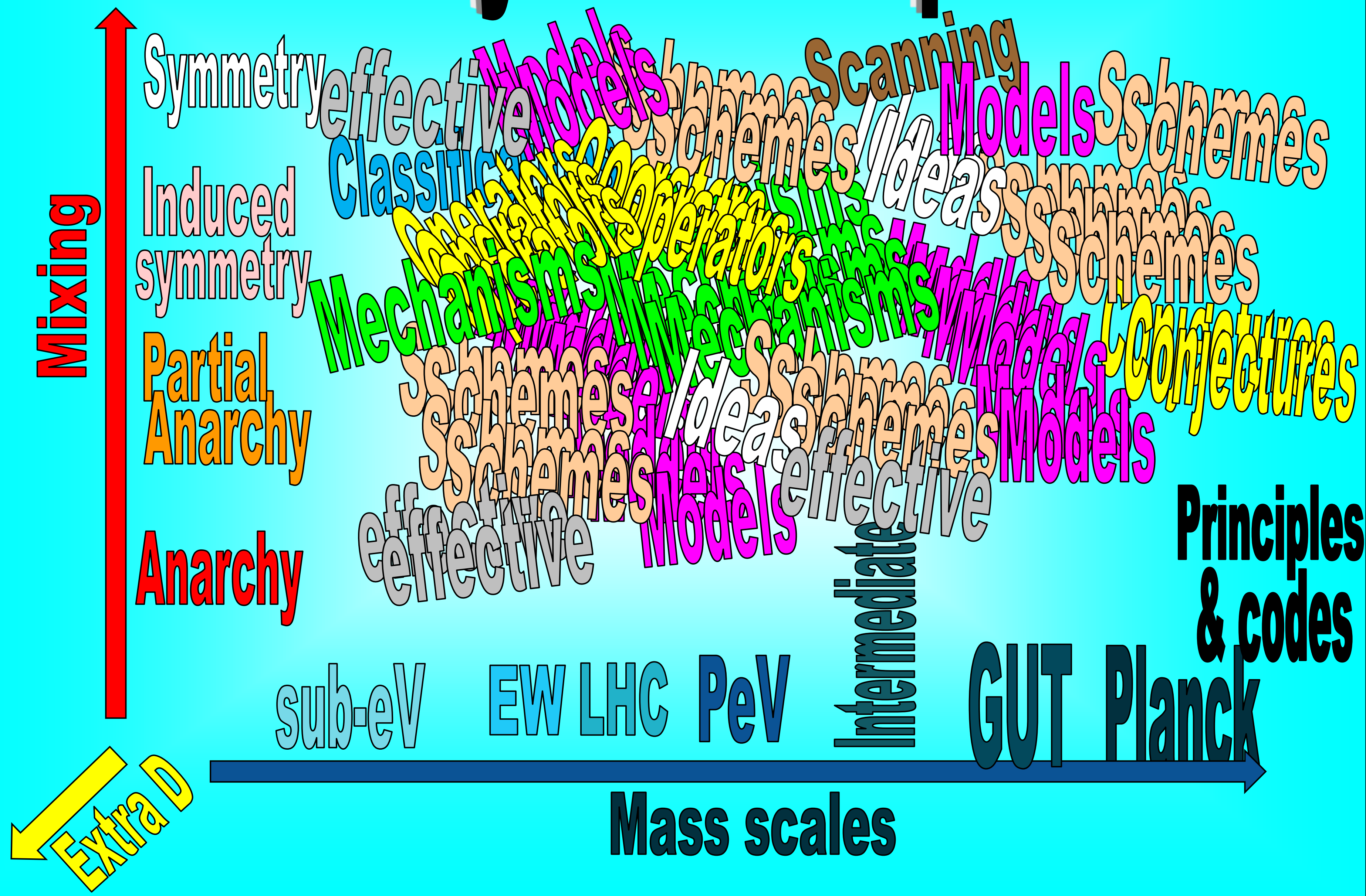
Davis’s remark on ν models- DM connection has new turn now:

- joint models of neutrino masses and dark matter
- understanding neutrino properties can steam from the Dark sector of theory

"Theory" Landscape

Multi dimensional

Theoretical studies



What is the problem?

No theory of flavor, in general

No theory of quark masses and mixing

No physics BSM has been discovered yet at LHC …
Especially no SUSY → UV completion issue.

What is the hope?

Neutrinos are the key

Less ambitious:

It the neutrino which shed the light on all these problems

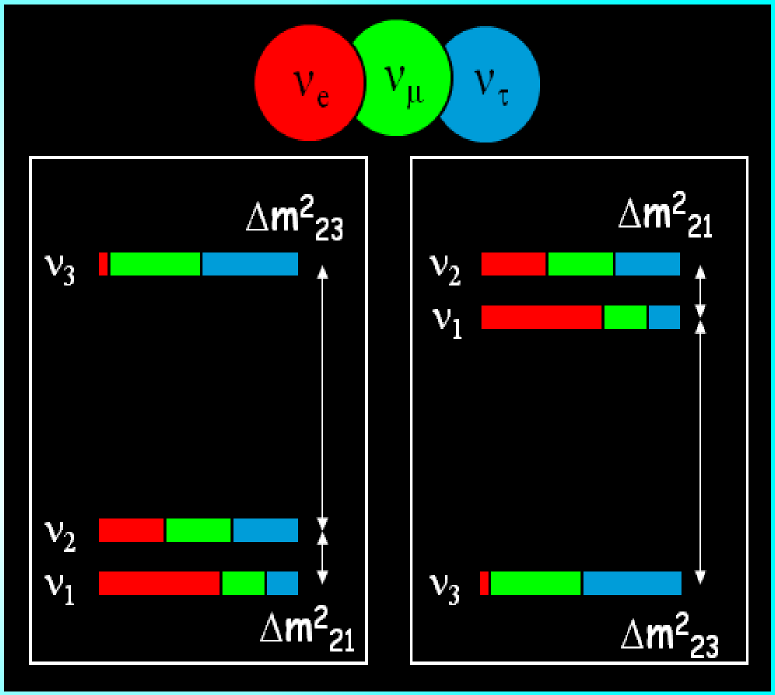
Understand at least the difference of neutrino mass and mixing from quark mixing and masses

What we really know

3ν - paradigm

All well established/confirmed results fit well a framework

- three neutrinos
  - with interactions described by the standard model
  - with masses and mixing
- negligible feedback of neutrino mass generation on the standard model



The theory?

$$\frac{1}{\Lambda} LLHH$$

S. Weinberg

Large scale
of new physics

Violation of
universality,
unitarity

or maybe: $h\, H\, \bar{L} \nu_R\, H$

That's all?
Will we learn more?

Outline

1. Sterile neutrinos – the key?
2. Nature of neutrino mass
3. Neutrino mass and EW scale
4. Symmetry behind mixing pattern
5. Quarks and leptons, Unification
6. Neutrino portal to dark sector
7. Neutrino connections

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

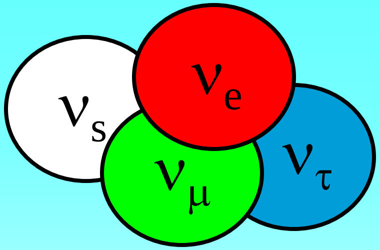
Naturally small Dirac masses → require additional symmetry, new fermions, scalars

E.Ma , 2016

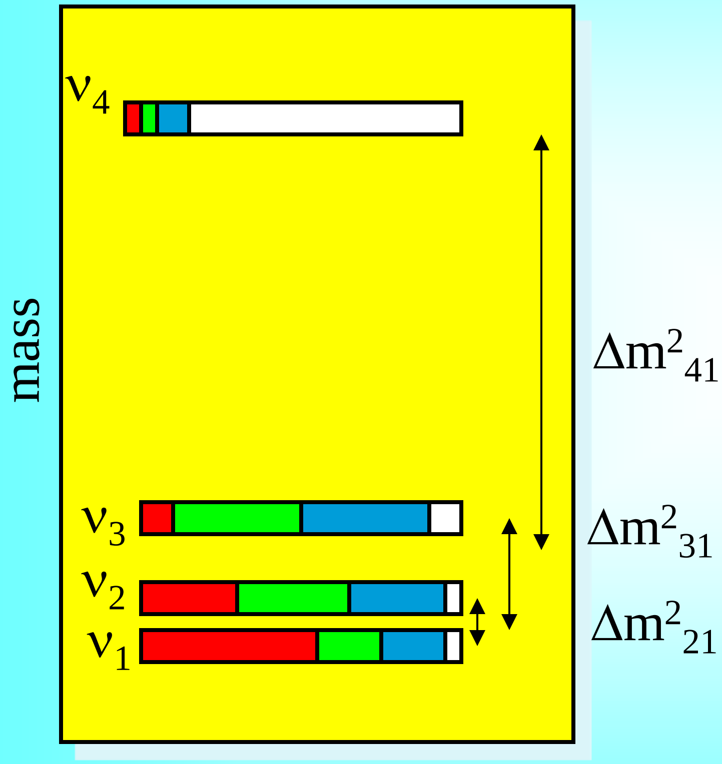
May take some (a lot of) time

Sterile neutrinos

(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

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

eV scale seesaw

$$m_a = \begin{pmatrix} 0.2 & 0.4 & 0.4 \\ \dots & 2.8 & 2.0 \\ \dots & \dots & 3.0 \end{pmatrix} 10^{-2}\ \text{eV}$$

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

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

Nature of neutrino mass

is the neutrino mass of
the same origins as masses
of other particles?

Two aspects

Similar to cosmological constant

Smallness:

Suppression wrt. the EW scale

Why there is no usual scale Dirac masses?

No RH component → Dirac mass can not be formed

symmetry

See-saw or multi-singlet mechanisms
- suppression only
- finite contribution negligible

Finite value

Mechanisms unrelated to suppression of usual Dirac masses

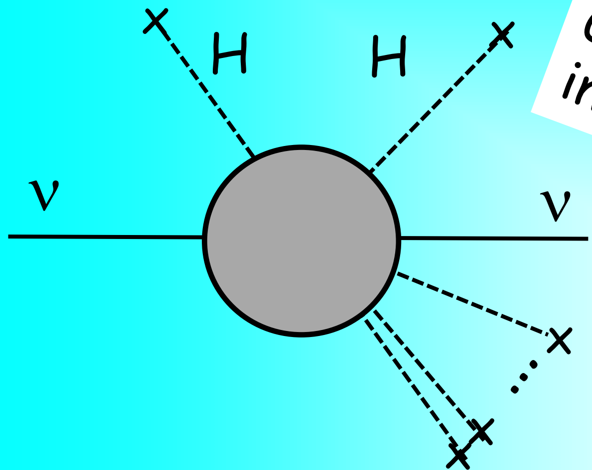
Seesaw type II

Radiative mechanisms

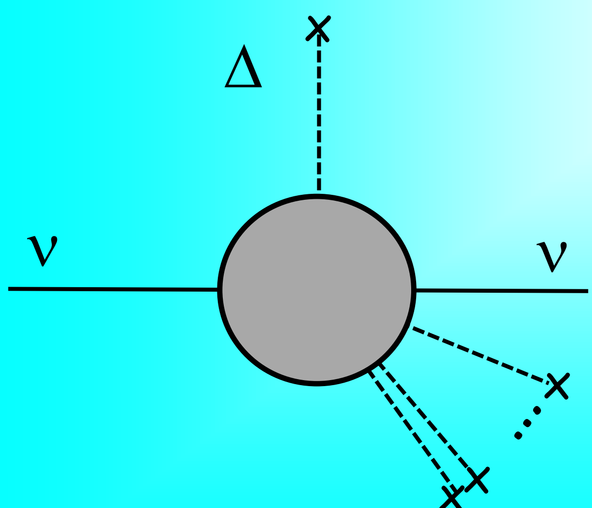
see-saws type-I does both things simultaneously:

incomplete suppression

Origins of (finite) mass



Gauge invariance



Similarly for Dirac neutrinos

Hard mass related to the EW scale

small effective coupling

small induced VEV formed by large VEV's (seesaw II)

Soft mass VEV created at small scales

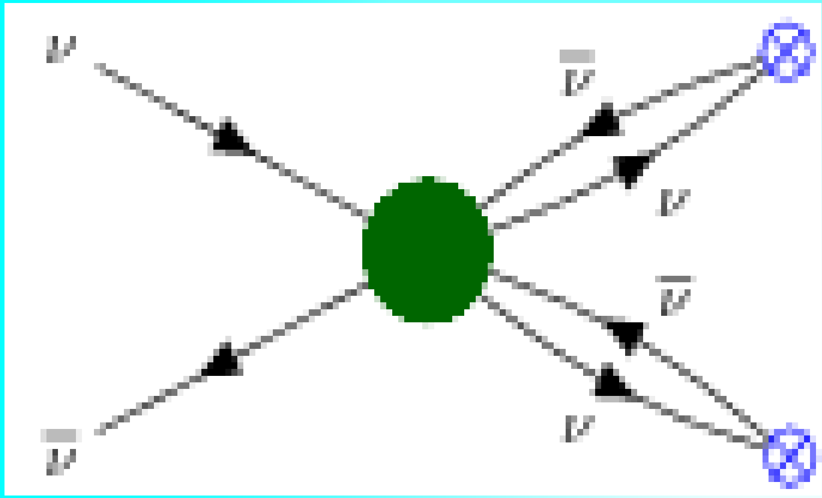
melting at T ~ VEV

MAVAN Environment dependent masses; relic neutrinos

Gravitationally induced mass

Melting couplings

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

Probing Nature of neutrino mass

Determination of masses, mass squared differences from processes at different conditions

Searches for dependence of mass on external variables:

Vacuum – media with different densities, fields

Solar – KamLAND: Δm_{21}^2

2-3 mixing: T2K - NOvA

Energies (in medium, or if Lorentz is violated)

Epochs (red shifts)

MAVAN

Momentum transfer

Virtuality: On shell – off shell

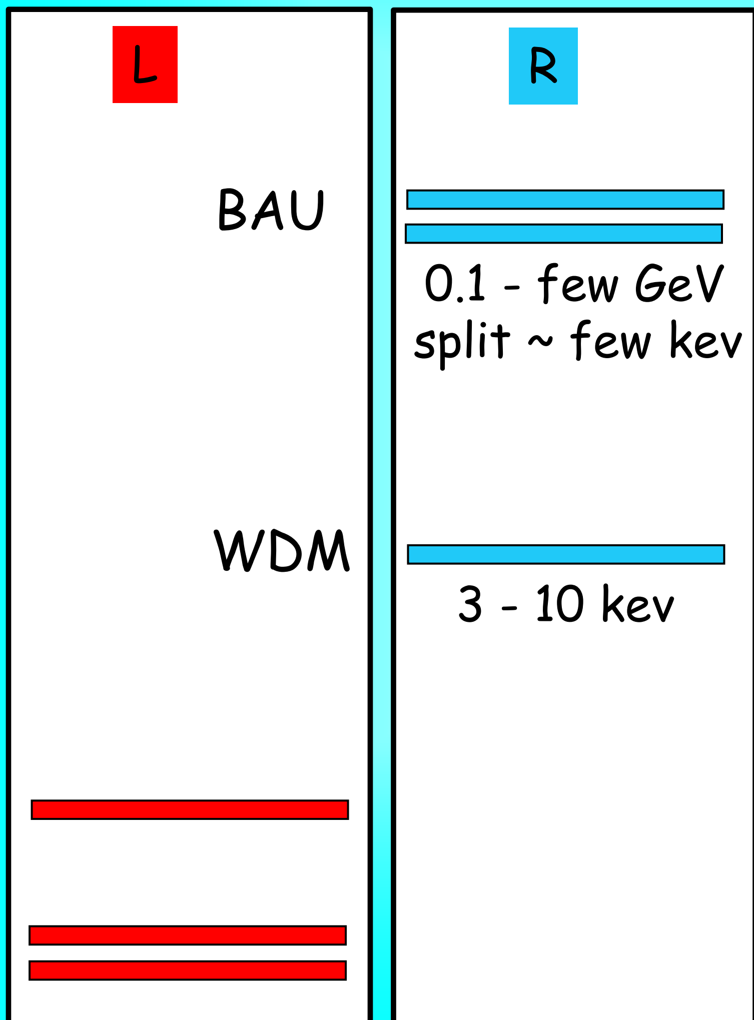
Neutrinoless Double beta decay – unique?

Neutrinos and EW scale

νMSM

M. Shaposhnikov, et al

Everything below EW scale
→ small Yukawa couplings



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

etc, SHiP

Origin of this scale, Why at EW?

- radiative decays → 3.5 keV line?

Decouples from generation of neutrino mass, RHN?

Extensions of model
G.K Karananas, M. Shaposhnikov

Unification: Constrained GUT's?

Unnatural Seesaw –small Dirac Yukawas

Flavor structure, mixing?

Left-right models

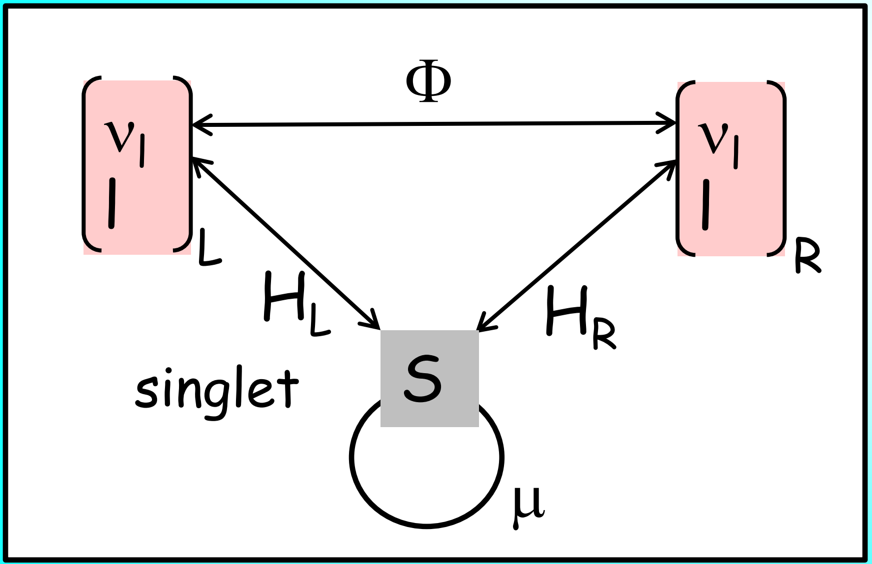
With inverse seesaw

Natural realization of low scale seesaw

If low scale – small Dirac Yukawa couplings

Usual coupling – inverse seesaw

$m_D = h \langle \Phi \rangle$ $M_R = h_R V_R$



kev scale

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_R^T \\ 0 & M_R & \mu \end{pmatrix} \begin{matrix} \nu_L \\ \nu_R \\ S \end{matrix}$$

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

$m_D = m_q$

→ embedding in SO_{10}

B. Dev, R Mohapatra

flavor symmetry in μ

$M_L = h_L V_L$ $V_L \ll V_R$ is required

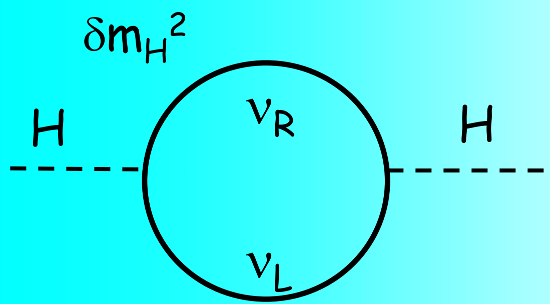
ν- mass and Higgs physics

bottom -up

Correction to Higgs mass

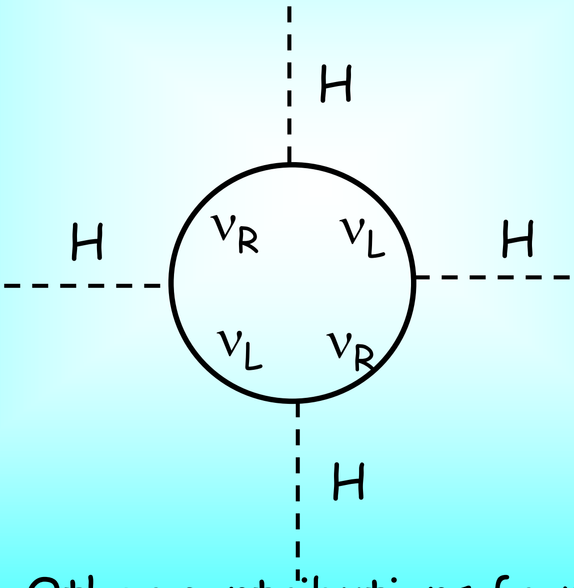
Correction to λ - 4 point coupling – vacuum stability

Higgs as composite state of neutrinos



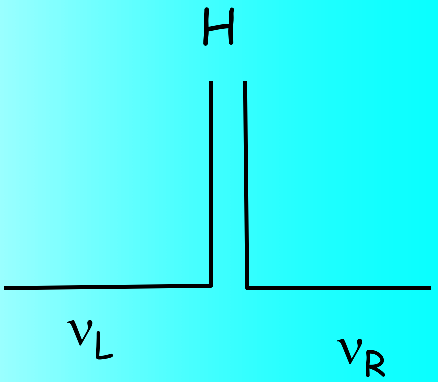
Upper bound on mass
$M_R < 10^7$ GeV
→ leptogenesis ?
→ cancellation (a kind of SUSY)

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



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

C. Bonila et al, 1506.04031



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

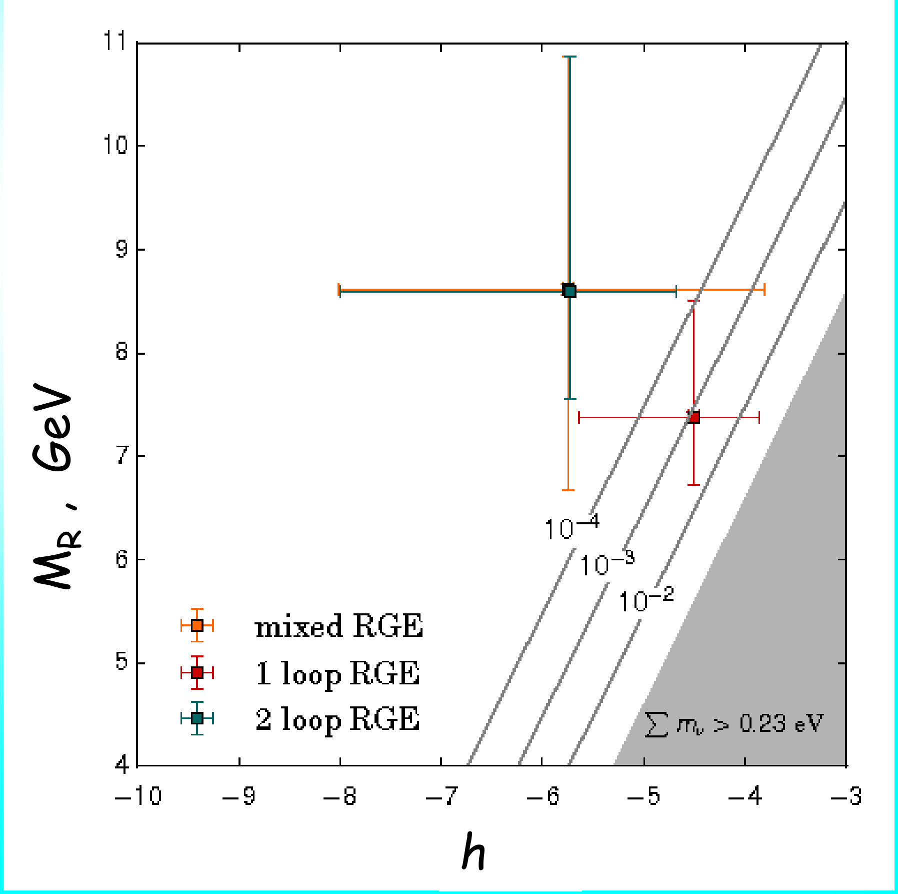
Both Higgs mass term and quartic coupling (absent at tree level) are generated by neutrino loops

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



Symmetry behind mass and mixing

Mixing and symmetry

Real or accidental?

Tri-bimaximal mixing

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

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

0.15

0.62

0.78

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

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

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

Tests:

Sum rules... But in most of situations – just accidental,
rather than follow from symmetries

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

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

Residual symmetries approach

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

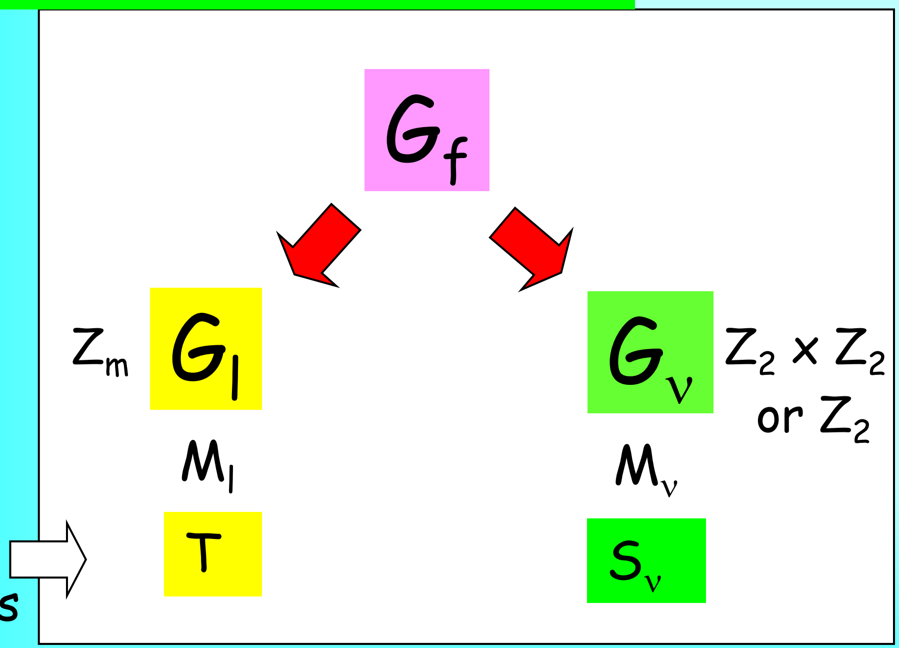
Mixing appears as a result of different ways of the flavor symmetry breaking in the neutrino and charged lepton (Yukawa) sectors.

No connection of masses and mixing

A_4 S_4 T_7 T'

Residual symmetries of the mass matrices

Symmetry transformations in mass bases



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

Generic symmetries which do not depend on values of masses

CP-transformations can be added

Discrete finite groups
Flavons to break symmetries

Flavons

Intrinsic symmetries

Realized for arbitrary values of neutrino and charged lepton mass

- for Majorana neutrinos

in the mass basis

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

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

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

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

$\Sigma \phi_\alpha = 0$

Intrinsic = 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

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

p -integer

Symmetry group condition

D. Hernandez, A.S. 1204.0445

For each i the equation gives two relations between mixingparameters

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

$Z_2 \times Z_2$ → TBM

Example

$G_\nu = Z_2$ Two relations

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

In the residual symmetries approach

for column of the mixing matrix:

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

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

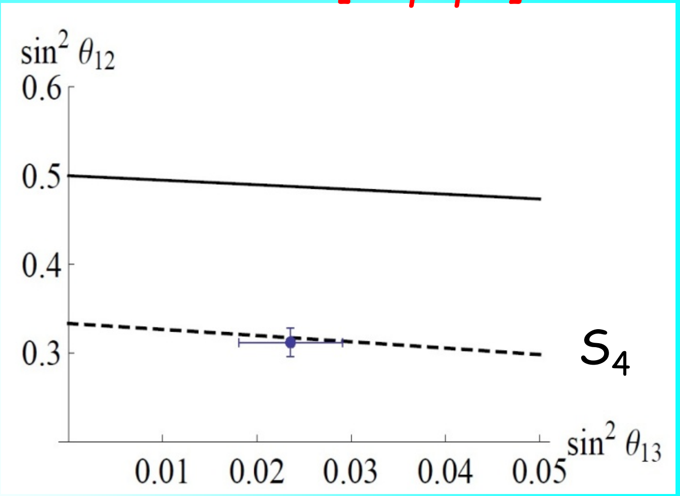
k, m, p integers which determine symmetry group

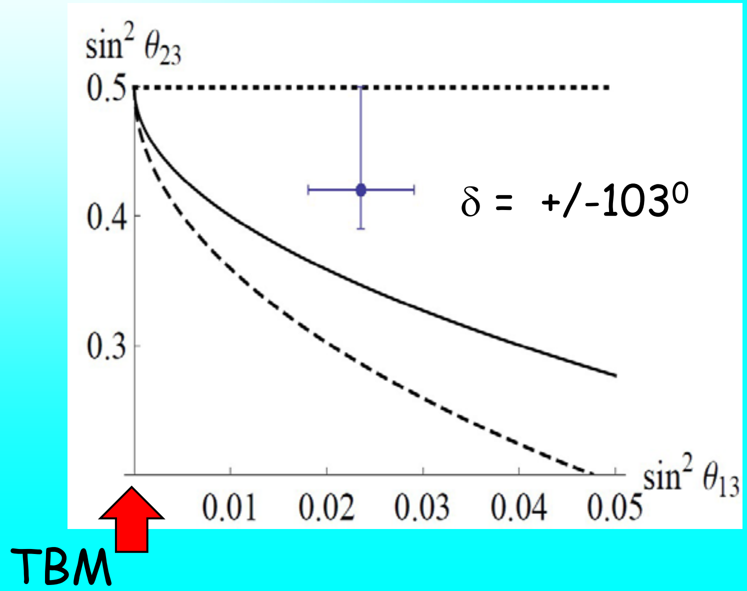
$k_\alpha = 0$

TBM$_1$

TBM$_2$

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





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

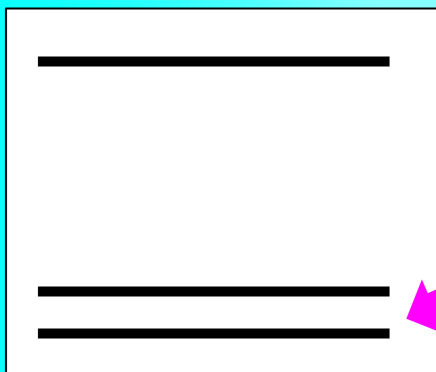
Mixing , Mass, hierarchy

BEHIND type of MH

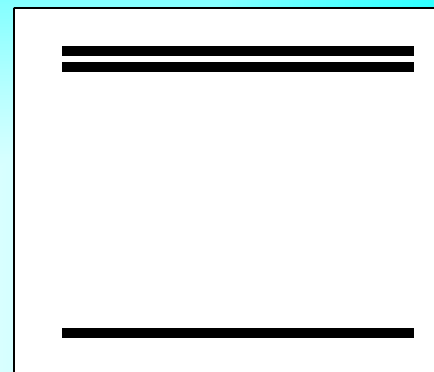
Fundamental: principle, symmetry

Accidental: selection of values of parameters

Quasi-degenerate → symmetry



degeneracy is possible



$$\frac{m_2}{m_3} \sim \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}} = 0.18$$

$$\theta \sim \sqrt{\frac{m_2}{m_3}}$$

the weakest hierarchy

$$\frac{\Delta m}{m} \sim \frac{\Delta m_{21}^2}{2\,\Delta m_{32}^2} = 1.6\ 10^{-2}$$

Similar to quark spectrum

but 1-2 mixing strongly deviates from maximal
→ From charged lepton

See-saw

Quark-lepton symmetry

Unification

Pseudo-Dirac + 1 Majorana

Flavor symmetries

Broken $L_e - L_\mu - L_\tau$ symmetry

Quark and lepton Unification

Quark and Lepton Mixing

Patterns of mixing are strongly different

Non connected

Different mechanism of generation of masses of quarks and neutrinos

e.g. in seesaw type-II

Partially connected

QLC -relations

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

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

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

Predicted from QLC

Fully connected

by symmetry: difficult to realize

In general:

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

$U_{CKM} = V_{CKM}$

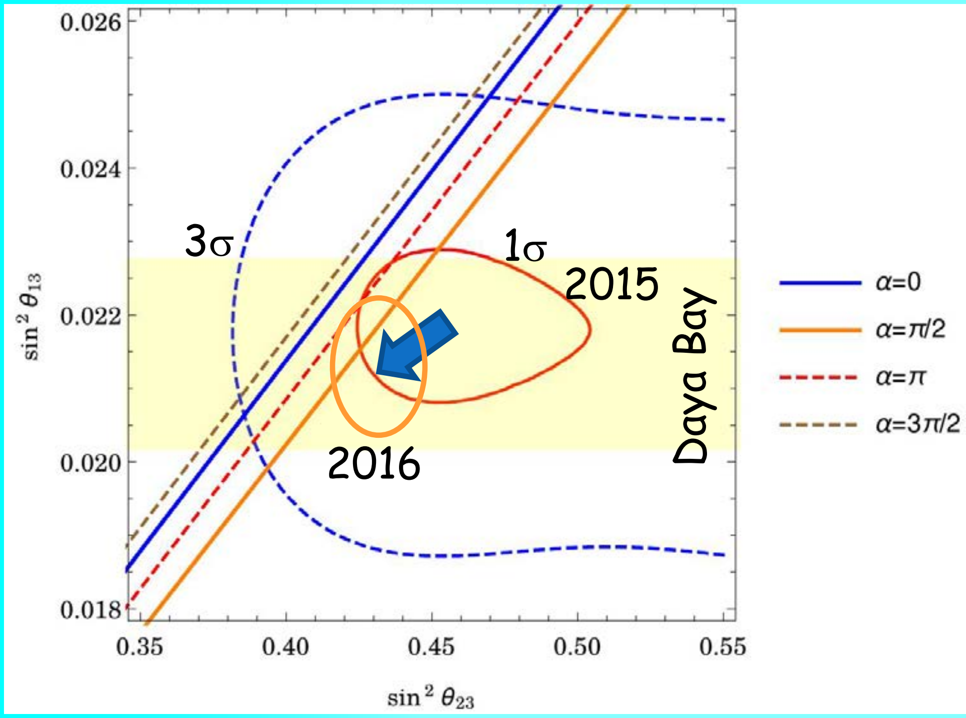
Bi-maximal or TBM matrix

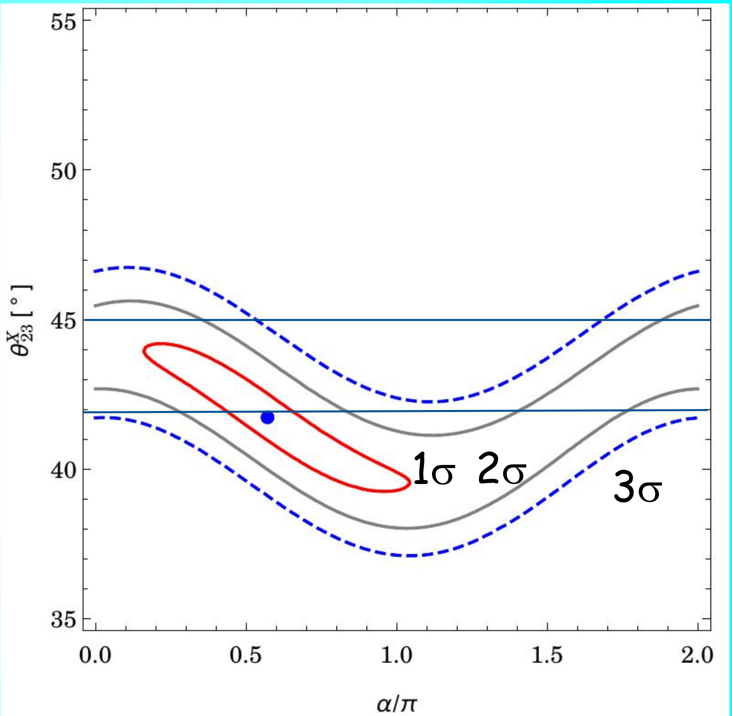
General relation

Normal mass ordering

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

$\lambda = \sin\theta_C$





Dependence of 1-3 mixing on 2-3 mixing for different values of the phase α. Allowed regions from the global fit NuFIT 2015

Allowed values of parameters of U_X
Best fit value: $\theta^X_{23} = 42^0$

RGE effect from maximal mixing value at high scale

Implications

Quarks and leptons know about each other,
Q L unification, GUT or/and
Common flavor symmetries

Some additional physics is involved in the lepton sector which explains smallness of neutrino mass and difference of the quark and lepton mixing patterns

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

Neutrinos and Unification

Another indication – smallness on neutrino mass

The simplest connection:

See-saw type-I

RH – neutrinos

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

$M_{3R} \sim M_{GUT} = 10^{16}$ 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?

Seesaw and PMNS-CKM relation

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

$$\begin{array}{c|cc} & \nu & N \\ \hline \nu & 0 & m_D \\ N & m_D^T & M_R \end{array}$$

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

N have large Majorana masses $M_R \gg m_D$

Diagonalization:

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

V_{CKM}^+

if $m_D = m_D^q$ — $(M_R)^{-1}$ should give U_x

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

More than usual see-saw?

Scale of see-saw

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

q – l similarity: $m_D \sim m_q \sim m_l$

for one third generations $M_R \sim 2\ 10^{14}$ GeV

M_R - hierarchy

$$M_R = - m_D^{diag} (m_{TBM})^{-1} m_D^{diag}$$

Quadratic hierarchy

Flavor structure

Difficult to reproduce

Can be explained in the framework of double seesaw

Double Seesaw

R.N. Mohapatra
J. Valle

Three additional singlets S which couple with RH neutrinos

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & M_S \end{pmatrix} \begin{bmatrix} \nu \\ \nu^c \\ S \end{bmatrix}$$

$M_S >> M_D$

M_S - scale of B-L violation

RH neutrinos get mass via see-saw

$$M_R = M_D^T M_S^{-1} M_D$$

This explains

1. strong mass hierarchy $M_D \sim m_D$ and M_S has no strong hierarchy
2. intermediate scale of masses if $M_S \sim M_{Pl}$, $M_D \sim M_{GU}$
3. Flavor structure:

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

if $m_D = A\, M_D$ ⇒ $m_\nu \sim M_S$ may have certain symmetries

A.Y.S
M. Lindner,
M.A. Schmidt
A.Y.S

Neutrino portal to the Dark sector

Neutrino portal

Neutrino are special

via the portal:

Neutrino mass - seesaw

Large lepton mixing

Non Standard Interactions

SM is well protected

$\bar{L}H$ F

LH

ν_R

S

ν_R

S

Dark sector

Singlet of SM symmetry group

F - fermionic operator

Non-local interactions

Interactions which violated fundamental symmetries

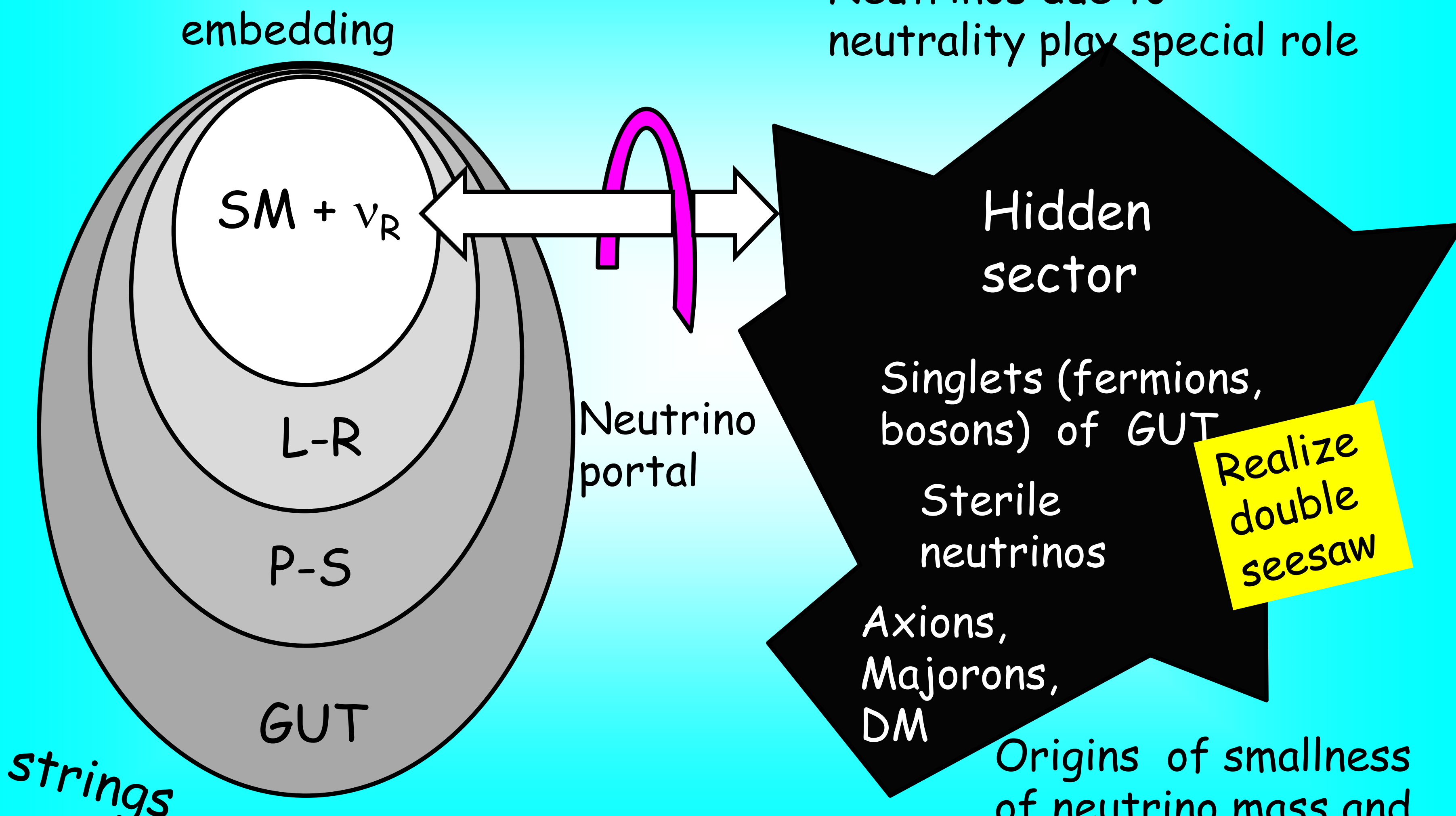
Singlet of symmetry group of hidden sector

$$\frac{1}{\Lambda^{n(F)\,-\,3/2}}\; L\, H\, F$$

Connection to the Higgs portal: H^+H

Mass and mixing from Hidden world

Neutrinos due to neutrality play special role



Origins of smallness of neutrino mass and large (maximal mixing)

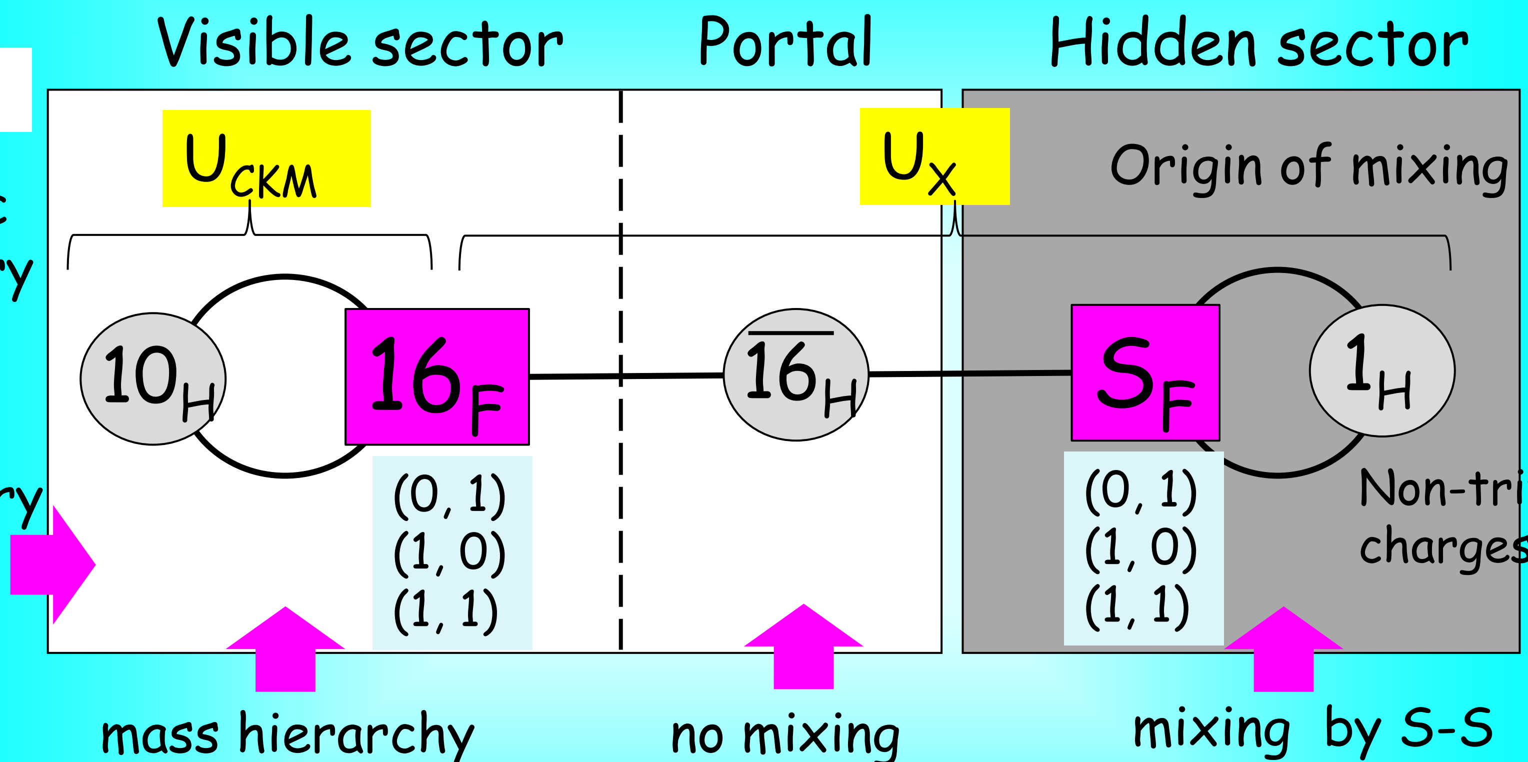
Realization scheme

Patrick Ludl, A.S
arXiv:1507.03494 [hep-ph]

SO(10)

Intrinsic symmetry

→ basis fixing symmetry $Z_2 \times Z_2$



due to non-trivial $Z_2 \times Z_2$ charges of 1_H

$m_D \sim M_D = \text{diag}$

$M_X = d^T M_S d$

Double seesaw

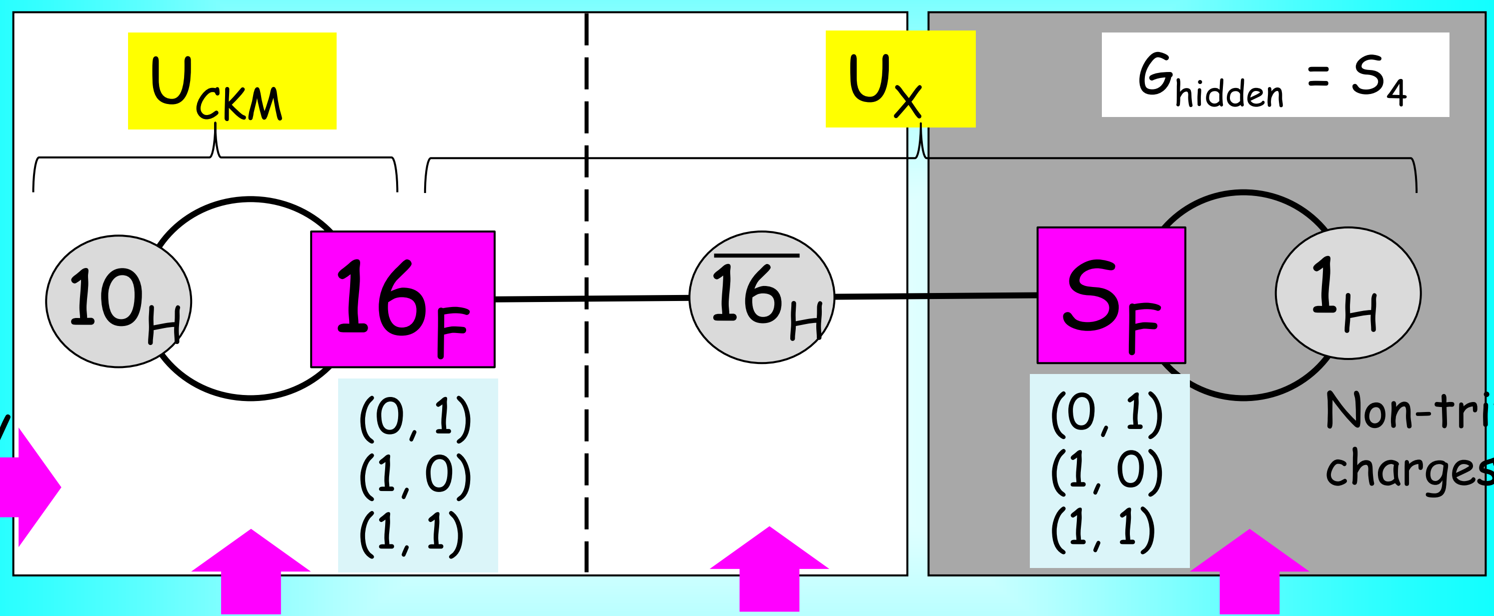
$M_S \sim$ non-diagonal, can be further structured by Non-abelian G_{hidden}

A scheme with $G_{hidden} = S_4$

Xun-Jie Xu , A.S
in preparation

SO(10)

Visible sector — Portal — Hidden sector



basis fixing symmetry $Z_2 \times Z_2$

Non-trivial charges

mass hierarchy

no mixing

$Z_2 \times Z_2 \subset S_4$

Spontaneously broken by flavons

SKM mixing - additional structure

$m_D \sim M_D = diag$

$M_X = d^T M_S d$

Double seesaw

$M_S \sim M_{TBM}$

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

Neutrino Connections

Connections

Any discovery in these fields
can have impact on neutrinos

Neutrinos

LHC observables

Higgs physics

Dark matter

Lepton
Flavor
Violation

Anomalies
In B-decays Lepton
universality

$(g\text{-}2)_\mu$

Dark energy

Axions

Model dependent,
not unique

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

in conclusion

After more than 40 years of theoretical studies, thousands of papers written we are not far from the beginning: "ground zero" determined by experimental measurements

Big temptation to present such a talk as collection of jokes, if not one point

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

And all this is to measure neutrino parameters

Determination of neutrino parameters is not the end of story

We measure neutrino parameters to establish the underlying physics.

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

Back-up

Probably correct elements of the theory of neutrino mass and mixing are already among numerous mechanisms, schemes models 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

We discuss matrix elements, cross-sections, systematics, backgrounds....

to measure neutrino parameters

We measure neutrino parameters to establish the underlying physics.

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

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

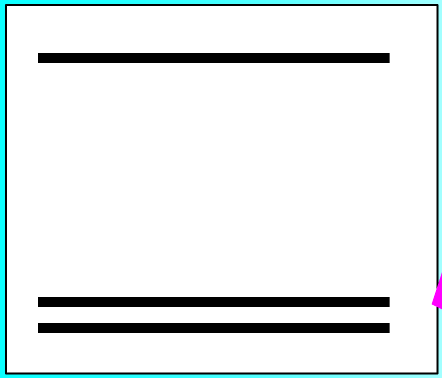
Mass and Mixing

In general

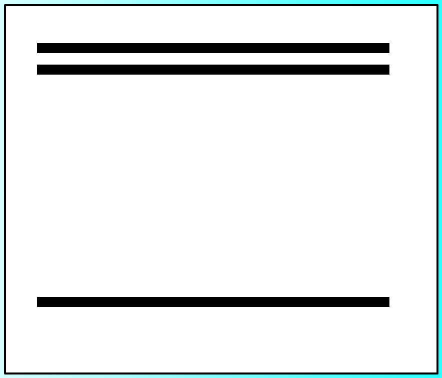
Maximal mixing ⟺ degeneracy of masses

This works for 1-2 Sector for both hierarchies:

Charged Lepton mixing explains deviation from maximal



Still degeneracy is possible



quark sector relation Still possible

2-3 mixing is close to maximal but 2-3 mass splitting is large. Complete degeneracy is disfavored by cosmology

Simple symmetries → degeneracy, massless states

$$\theta \sim \sqrt{\frac{m_2}{m_3}}$$

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

➡ Different mechanism of generation of masses of quarks and neutrinos

Partially connected

e.g. in seesaw type-II

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

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

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

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