Rabi's scenarios for neutrino mass and a "big picture"

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Rabi-fest, October 21, 2022

Scenario for neutrino mass

L-R Seesaw
GUT (or kind of the q –l unification)
SUSY (in some form)

➡ Neutrinos are Majorana

Rabi's criteria	Natural Plausible Testable

Understanding neutrino mass and mixing requires larger framework

➡ **a "big picture"**

Content

L-R seesaw and its incarnations

Embedding into big picture

Status, challenges and perspectives

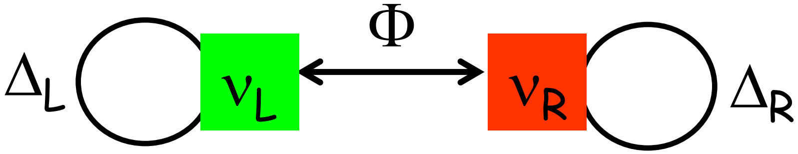
Seesaw and incarnations

From L-R to see-saw

R. N. Mohapatra and G. Senjanovic, PRL 44, 14 (1980) 912

Explanation of smallness of neutrino mass in $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Key: Higgs triplets Δ_L, Δ_R instead of doublets



$m_D = h_1 <\Phi>$ $M_R = h_3 <\Delta_R>$

Φ is bi-doublet

$<\Delta_R>$ ➡ $M_R = h_3 <\Delta_R>$

➡ $m_{W_R} = g <\Delta_R>$

$M_R \gg m_D$ $<\Delta_L> = 0$

$$m_\nu = - \frac{(h_1 <\Phi>)^2}{M_R} = \frac{g\,(h_1 <\Phi>)^2}{h_3\, m_{W_R}}$$

Seesaw scale is determined by the scale of L- R symmetry violation.

Smallness of neutrino mass is related to the suppression of the RH weak interactions

L-R seesaw

Minimal?

If $\langle\Delta_L\rangle \neq 0$ → seesaw type II

In general: seesaw type I + II more parameters/ freedom

Where are Higgs doublets? Why Nature starts with higher representation – should be a good reason?

Possible explanation: no elementary scalars

Higgses – composite states made of fermion doublets F_L, F_R

$\Delta_L = (F_L\ F_L)$, $\Delta_R = (F_R\ F_R)$, $\Phi = (F_L\ F_R)$

But in the Nambu Jona-Lasinio approach – no parity violation

E. K. Akhmedov, et al
PRD 53 (1996) 2752,
PLB 368 (1996) 270

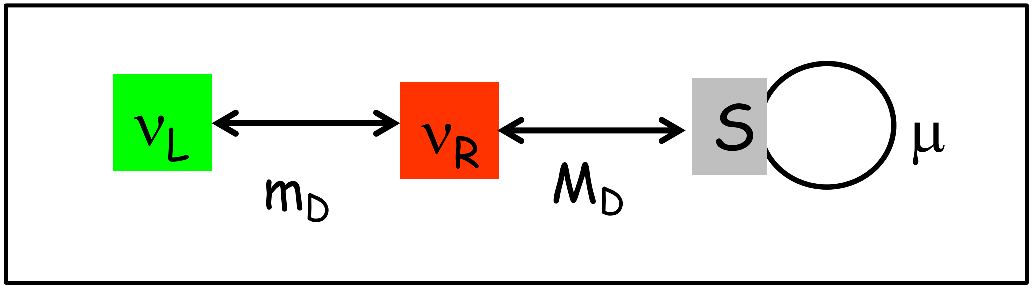
New fermions instead Higgs triplets:
Scheme: L, R doublets (+ bi-doublet) + new fermions

Extended seesaws

R. N. Mohapatra, PRL 56, 6, (1986) 561

R. N. Mohapatra and J W F Valle PRD 34, 5, (1986) 1642

New fermions – singlets of L-R symmetry



$M_R >> m_D$

No representations/interactions which give Majorana mass of ν_R

In M paper S = gauge fermion: mixture of SUSY partner of W_{3R} and Z_{B-L} . μ can be generated radiatively in 2 loops?

In M –V paper: S is singlet of $E_6 \times E_6$

One needs to start with superstrings, Calabi-Yao compactification, Ten dimensional $E_8 \times E_8$ Yang-Mills theory, symmetry breaking ... to arrive at neutrino mass matrix

Double seesaw and inverse seesaw

Mass matrix in the basis (ν, ν^c, S):

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & \mu \end{pmatrix}$$

for 3 generations three S
or 3 combinations of many S

$\mu \gg M_D$ - double seesaw

RH neutrinos get mass via see-saw $M_R = M_D^T \mu^{-1} M_D$

$\mu \sim M_{Pl}$, $M_D \sim M_{GUT}$

$\mu \ll M_D$ - inverse seesaw

ν^c, S form pseudoDirac neutrino with mass M_D

In both cases for light neutrinos $m_\nu = m_D^T M_D^{-1T} \mu M_D^{-1} m_D$

If $m_D = A M_D$ (A = const) → $m_\nu = A^2 \mu$

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

Structure of m_ν is determined by μ, it does not depend on the Dirac mass matrix structure (Dirac screening)

LHC-filic L-R models

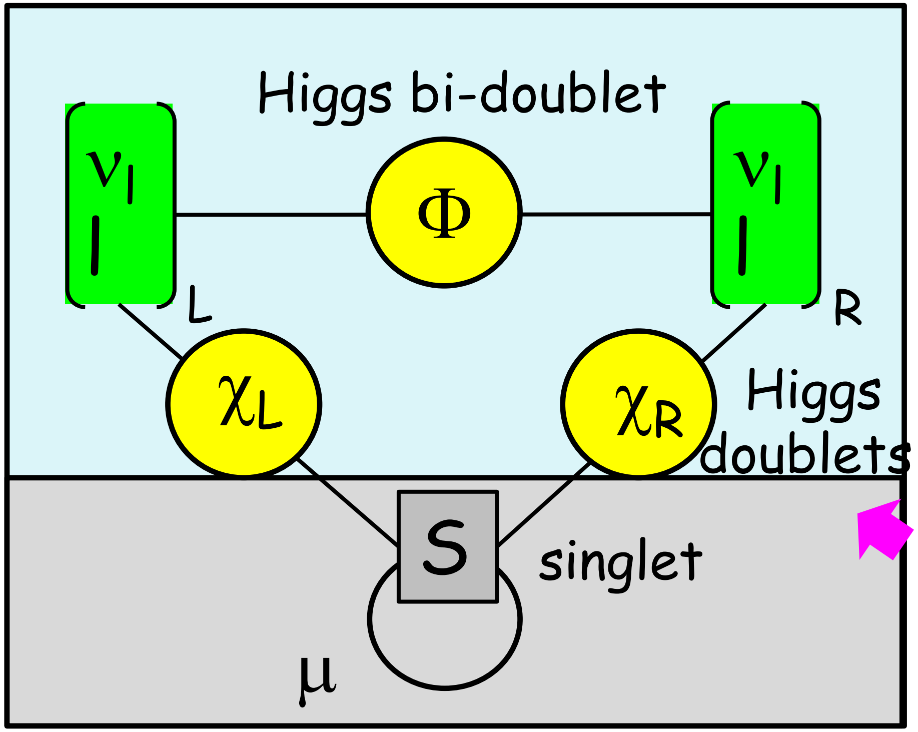
P.S.Bhupal Dev,
R.N. Mohapatra,
0910.3924 [hep-ph]

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

with GUT embeddings

with q-l similarity $m_q \sim m_l \sim m^D{}_\nu$

V.Brdar, A. Yu.S
JHEP 02 (2019) 045



Higgs bi-doublet

Φ

ν_l
l
L

ν_l
l
R

χ_L

χ_R

Higgs doublets

S

singlet

μ

Dark sector

breaks L-R symmetry

with Majorana mass terms

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

inverse seesaw

$M_D \sim M_R \sim$ PeV

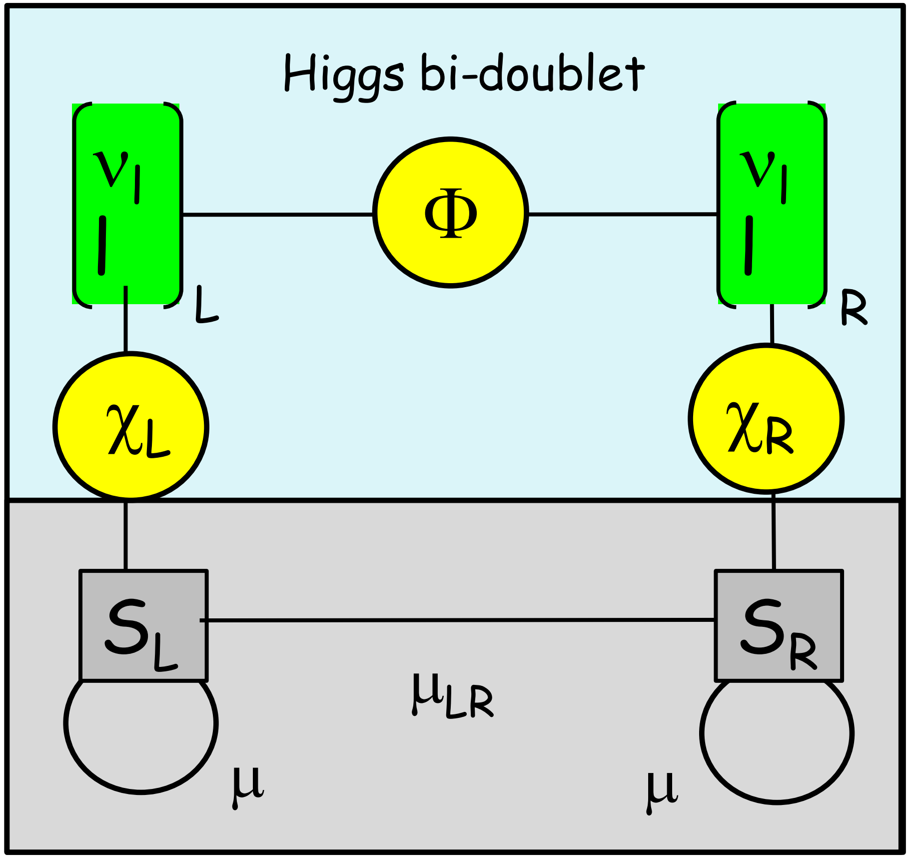
$\mu \sim$ 10 keV

flavor symmetry in μ

Model with L and R singlets

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

V.Brdar, A. Yu.S
JHEP 02 (2019) 045
1809.09115 [hep-ph]



invariant under global U(1)
broken by μ-terms

keV scale sterile neutrino
- DM

Local or Global? Majoron

In L-R $U(1)_{L+R} = U(1)_{B-L}$ local symmetry

R.N. Mohapatra and R.E. Marshak
PRL 44, 20 (1980) 1316

Y. Chikashige R.N. Mohapatra and R. D. Peccei
PLB, 4 (1981) 265, PRL 45, 24 (1980) 1926

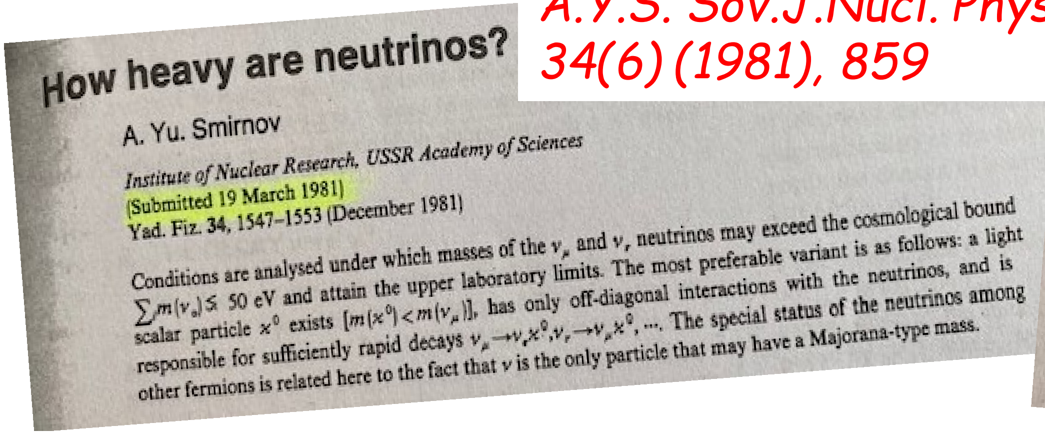
Lepton number is spontaneously broken global symmetry

→ Goldstone boson = Majoron

Rich phenomenology, long range forces, neutrino decay, $\beta\beta_{0\nu}$ - decay, Supernova neutrinos, DM ...

Neutrino decay into light or massless scalar

A.Y.S. Sov.J.Nucl. Phys.
34(6) (1981), 859

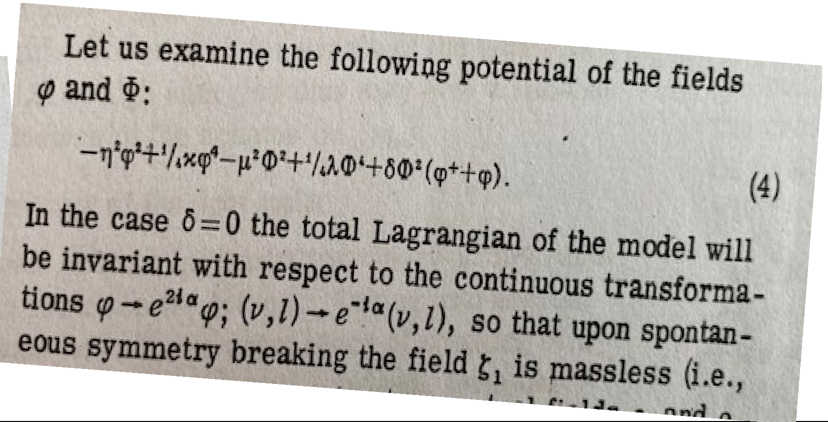


How heavy are neutrinos?

A. Yu. Smirnov

Institute of Nuclear Research, USSR Academy of Sciences
(Submitted 19 March 1981)
Yad. Fiz. 34, 1547–1553 (December 1981)

Conditions are analysed under which masses of the ν_μ and ν_τ neutrinos may exceed the cosmological bound $\sum m(\nu_a)\lesssim 50$ eV and attain the upper laboratory limits. The most preferable variant is as follows: a light scalar particle $\varkappa^0$ exists $[m(\varkappa^0)<m(\nu_\mu)]$, has only off-diagonal interactions with the neutrinos, and is responsible for sufficiently rapid decays $\nu_\mu\to\nu_e\varkappa^0, \nu_\tau\to\nu_\mu\varkappa^0, \ldots$. The special status of the neutrinos among other fermions is related here to the fact that ν is the only particle that may have a Majorana-type mass.



Let us examine the following potential of the fields φ and Φ:

$$-\eta^2\varphi^2+{}^1/_4\varkappa\varphi^4-\mu^2\Phi^2+{}^1/_4\lambda\Phi^4+\delta\Phi^2(\varphi^+ +\varphi). \qquad (4)$$

In the case $\delta=0$ the total Lagrangian of the model will be invariant with respect to the continuous transformations $\varphi\to e^{2i\alpha}\varphi$; $(\nu,l)\to e^{-i\alpha}(\nu,l)$, so that upon spontaneous symmetry breaking the field ζ_1 is massless (i.e.,

Seesaw and lepton mixing

Mixing pattern can be the key for understanding neutrino mass

Two facts: Large lepton mixing with certain pattern: ~TBM

Weak mass hierarchy, if any

Can be related

Seesaw enhancement of lepton mixing

Smallness of neutrino mass and large mixing have the same origin - seesaw

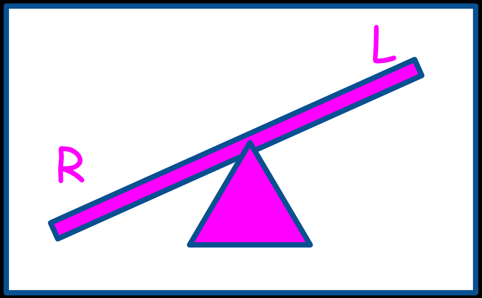
A Y S, Phys.Rev.D 48 (1993) 3264

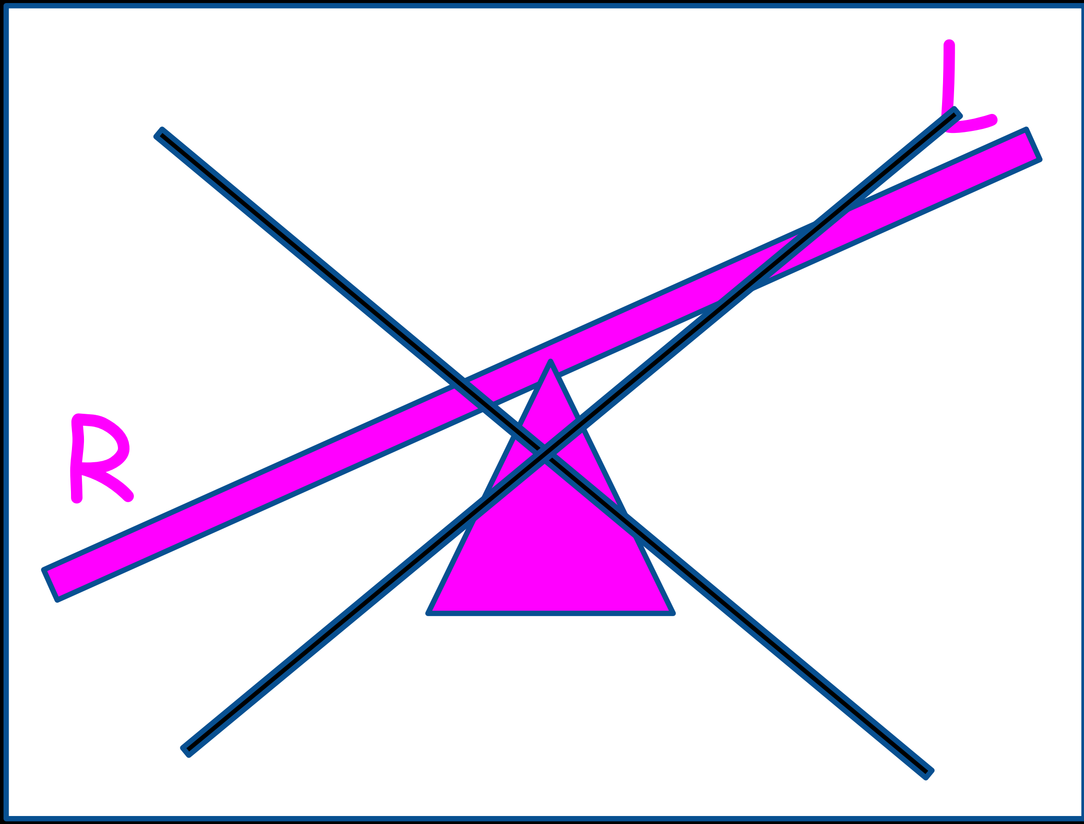
E. Akhmedov,
M. Frigerio,
AYS

Mixing → structure of neutrino mass matrix, properties, symmetries of m_ν $L_\mu - L_\tau$

Mixing, mass hierarchy (flavor physics), demand further extensions, big picture

A Big picture





A big picture

Understanding neutrino mass and mixing

Quark-lepton correspondence, symmetry, Unification, GUT

Flavor physics

SUSY

Anomalies

$(g-2)_\mu$

B- anomalies

Hubble tension

Connections:

Dark Matter

Baryon asymmetry of the Universe

Inflation

Quarks and Leptons. QLC

Similarity of mass hierarchy of quarks and charged leptons
Famous equality $m(b) = m(\tau)$ at GUT scale

Puzzle: strongly different patterns of quarks and lepton mixings

But relations: data

$$\theta_{12}^{l} \sim \pi/4 - \theta_{12}^{q}$$

$33.4^0 \sim 45^0 - 13^0$

$$\theta_{23}^{l} \sim \pi/4 - \theta_{23}^{q}$$

Lepton mixing ~ maximal minus quark mixing
Quark – lepton complementarity

H. Minakata , AYS

$$1 \gg \theta_{13}^{l} \gg \theta_{13}^{q}$$

The relations are approximate and at low energy scale.
Renormalization, corrections ...

Framework

$$U_{PMNS} = U_{lept}^{+}\, U_X$$

Common sector for quarks and leptons:

$U_{lept} \sim V_{CKM}$

From the "dark sector" coupled to neutrinos. Responsible for large neutrino mixing and smallness of neutrino mass

Implies
Q - L unification, GUT

CKM physics: hierarchy of masses and mixings, relations between masses and mixing

may have special symmetries which lead to BM or TBM mixing

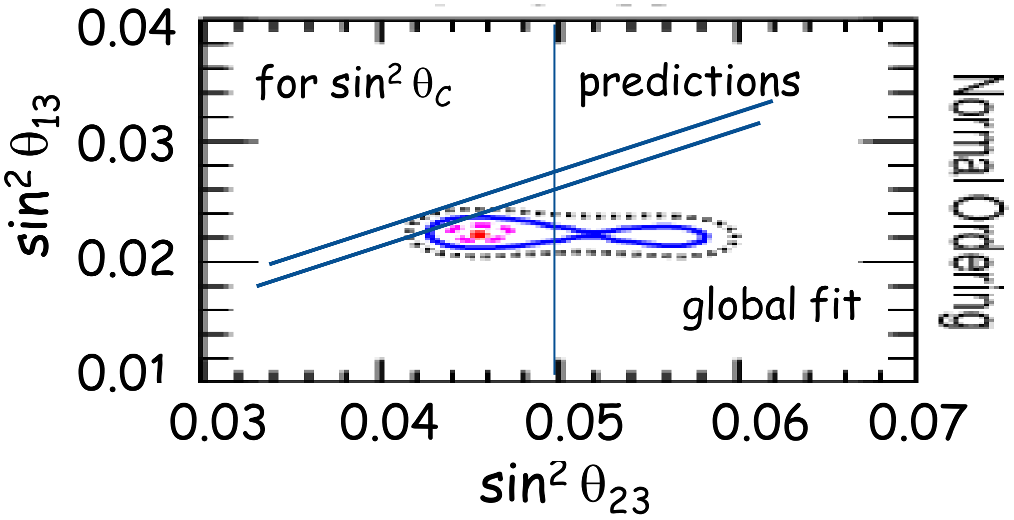
$U_X = U_{BM}\,,\, U_{TBM}$

→ easy to realize flavor symmetry

Prediction

for the 1-3 leptonic mixing: $\sin^2\theta_{13} \sim \frac{1}{2} \sin^2\theta_C$

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



θ_C - Cabibbo angle

Difference can be due to deviation of $\theta_{12}{}^l$ from θ_C related to difference of q and l- masses

Renormalization effects from GUT to low energies

Predictions for δ_{CP}^{l}

*B. Dasgupta, A Y.S. ,
N.P. B884 (2014) 357
1404.0272 [hep-ph]*

If $U_X = U_{BM}, U_{TBM}$, then $U_{lept} \sim V_{CKM}$ can be the only source of CP violation. Leads to the relation

$$\Rightarrow \quad \sin\delta_{CP}^{l} = -\sin\delta_{CP}^{q} \cos\theta_{23}^{l} \frac{\sin\theta_{13}^{q}}{\sin\theta_{13}^{l}} \qquad \frac{\lambda^3}{\lambda}$$

$\lambda = \sin\theta_C$

0.93 0.75 λ^2

$\sin\delta_{CP}^{l} \sim \lambda^2 \sim 0.046$ or $\delta_{CP}^{l} = 2.6^\circ$

CP phase: $\sim -\delta_{CP}^{l}$ or $\pi + \delta_{CP}^{l}$

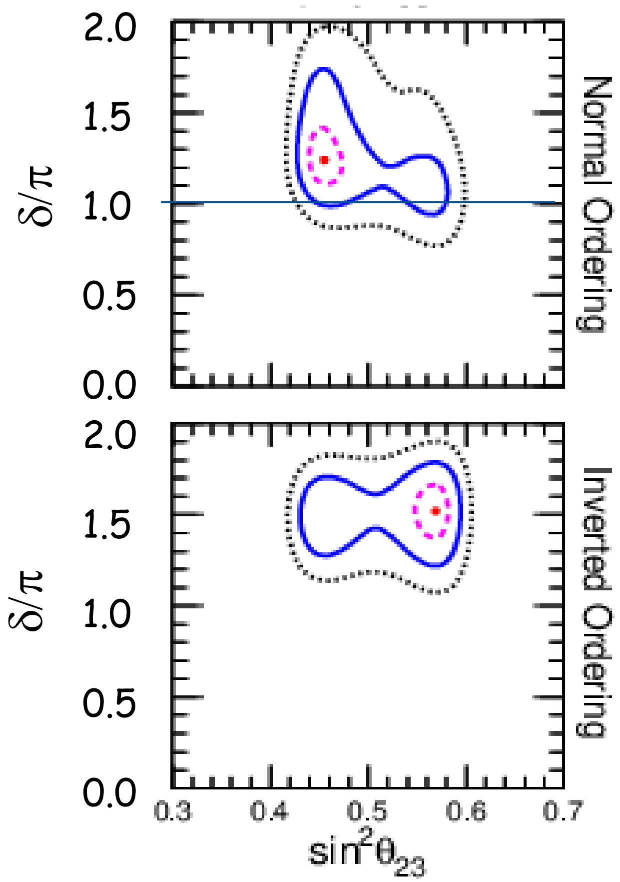
Leptonic CP is small because the leptonic 1-3 mixing is large

Experiment: CP-phase is close to π?

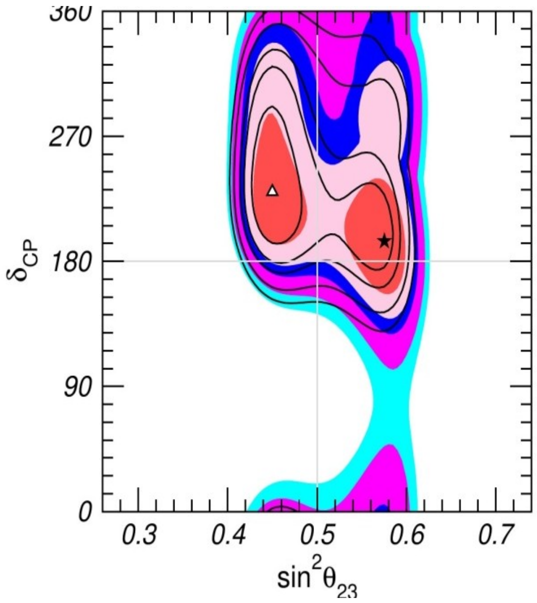
NOvA-T2K 2σ tension NOvA: $\delta_{CP} = 0.82\pi$, T2K $\delta_{CP} = 1.5\pi$

Global fits

F Capozzi, et al 2107.00532 [hep-ph]



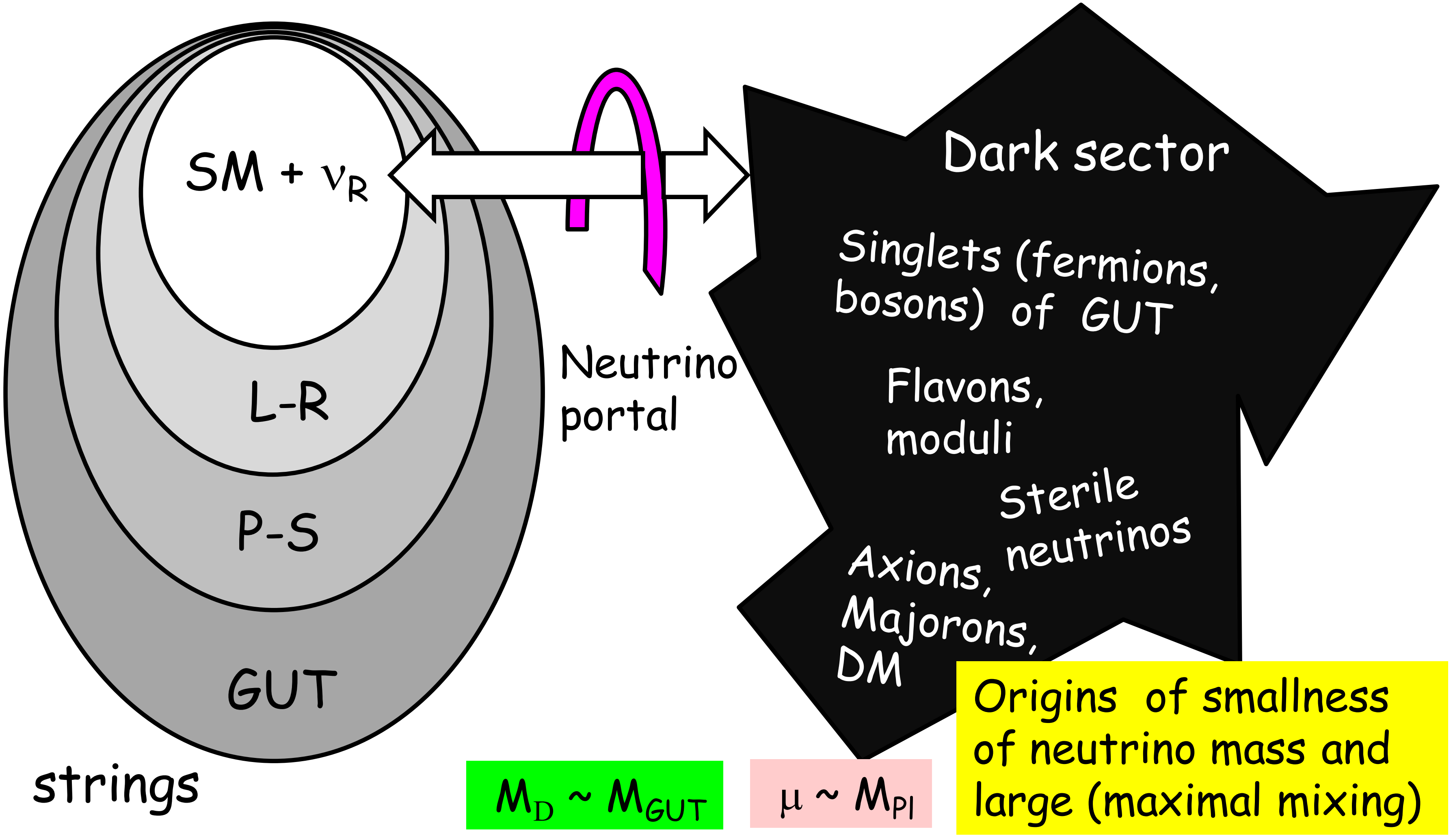
NuFIT 5.1 (2021), www.nu-fit.org



even closer to π

A scenario

From double seesaw to
neutrino portal and Dark sector



SM + ν_R

L-R

P-S

GUT

strings

Neutrino
portal

Dark sector

Singlets (fermions,
bosons) of GUT

Flavons,
moduli

Sterile
neutrinos

Axions,
Majorons,
DM

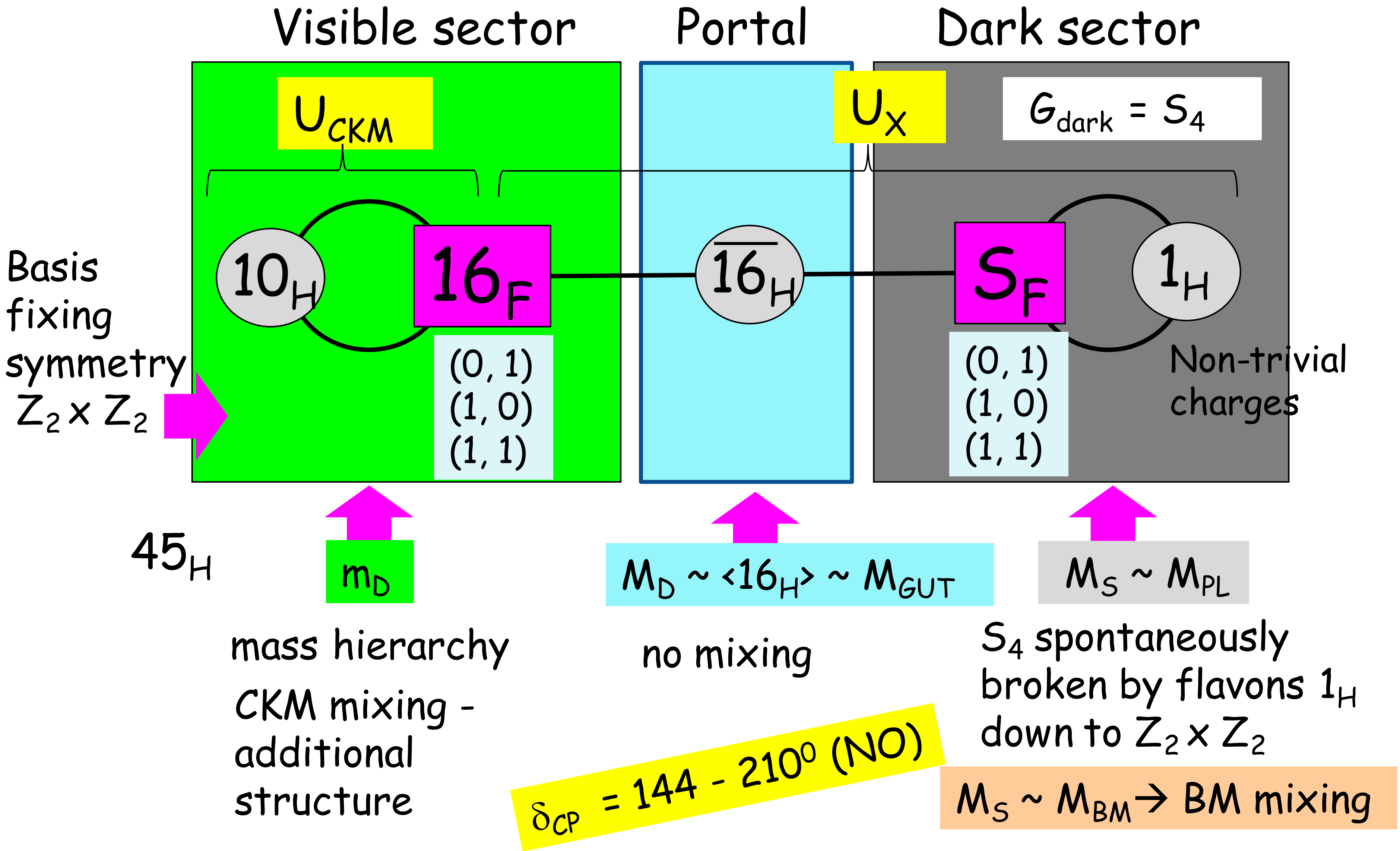
$M_D \sim M_{GUT}$

$\mu \sim M_{Pl}$

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

Realization in SO(10) GUT

Xun-Jie Xu , A.Y.S.
1803.07933 [hep-ph]



Visible sector

Portal

Dark sector

U_{CKM}

U_X

$G_{dark} = S_4$

Basis fixing symmetry $Z_2 \times Z_2$

10_H

16_F

$\overline{16}_H$

S_F

1_H

(0, 1)
(1, 0)
(1, 1)

(0, 1)
(1, 0)
(1, 1)

Non-trivial charges

45_H

m_D

$M_D \sim \langle 16_H \rangle \sim M_{GUT}$

$M_S \sim M_{PL}$

mass hierarchy

CKM mixing - additional structure

no mixing

S_4 spontaneously broken by flavons 1_H down to $Z_2 \times Z_2$

$\delta_{CP} = 144 - 210^0$ (NO)

$M_S \sim M_{BM} \rightarrow$ BM mixing

Status, challenges perspectives

Neutrino data and neutrino mass

Scenarios are in agreement with most of the data

Cosmology: $\Sigma_i \, m_{\nu i} < (0.09 - 012)$ eV

Quasi degenerate spectrum is excluded, $m_2 / m_3 < 0.5$ (NO), IO spectrum - disfavored

KamLAND-Zen , S. Abe et al.
2203.02139 [hep-ex]

$m_{ee}^0 < (0.05 - 0.156)$ eV (90% C.L.) touching IO band

NuFIT 5.1 (2021), www.nu-fit.org

$\sin^2\theta_{12}$ closer to 0.3, $\theta_{12} = 33^o$ consistent with the QLC value 32^o
Normal mass ordering is preferable by $(2 - 3\sigma)$

Deviation from maximal $|\Delta \sin^2\theta_{23}| = 0.05$, $|\Delta\theta_{23}| = 3^o$
Maximal mixing is disfavored at 2σ. First octant is preferred?

No dependence of neutrino parameters on neutrino energy, time, environment has been found

Sterile "damage". eV seesaw

$$\left(\begin{array}{ccc} \cline{1-2} \multicolumn{1}{|c}{m_{ee}} & \multicolumn{1}{c|}{\ldots} & m_{es} \\ \multicolumn{1}{|c}{\ldots} & \multicolumn{1}{c|}{\ldots} & \ldots \\ \cline{1-2} m_{es} & \ldots & m_{ss} \end{array}\right)$$

$m_{ss} = 1 - 3$ eV

$\sin^2 \theta_{es} \sim m_{es}/m_{ss} \sim 0.02 - 0.1$

BEST, Gallium,
LSND, MiniBooNE
Neutrino 4

Correction to the mass matrix of active neutrinos

$$\delta m = \sin^2\theta_S\, m_S \sim (0.02 - 0.3)\ \text{eV}$$

- at the level of largest elements (~ 0.03 eV) of the 3ν mass matrix

ν_S effect is not a small perturbation of 3ν picture and its symmetries

It requires cancellations, fine tuning (cancellation), and should be included in theory/symmetry constructions from the beginning

Rabi: smallest damage, if ν_S are mirror neutrinos

On the other hand it allows to explain difference of the quark and lepton mixings, large lepton mixing

Perspectives

High scale L-R seesaw

Indirect confirmations

No new physics at low scales

Proton decay

Low scale L-R seesaw

Inverse seesaw

Discovery of N_R , W_R , Δ^{++}

PseudoDirac heavy leptons

Confirmation of anomalies and their interpretations

Non-unitarity, non-universality

νMSM

Alternative mechanisms

Radiative

Sneutrino condensate

Discovery of new particles involved in ν mass generation

Completely different

Another nature
of neutrino mass

Effective mass due to refraction: ν scattering on background
Modification of dispersion relations → oscillations

Scenarios based on NSI with heavy mediators are excluded,
New possibilities - light mediators and light scatterers

Tests:

Dark Matter identification
Discovery very light scalars, dark photons

Neutrino condensation $\langle \nu\nu \rangle$

may emerge e.g. if gravity contains a non-zero topological vacuum susceptibility

Search for time, space dependence of oscillation parameters

Vacuum and properties of oscillations

G.Dvali , L Funcke,
1602.03191 [hep-ph]

Neutrino vacuum condensate due to gravity. Order parameter

$$\langle \Phi_{\alpha\beta} \rangle = \langle \nu_\alpha^T C \nu_\beta \rangle \sim \Lambda_G = \text{meV - 0.1 eV}$$

Cosmological phase transition at $T \sim \Lambda_G$

Neutrinos get masses, in flavor basis $m_{\alpha\beta} \sim \langle \Phi_{\alpha\beta} \rangle$
(charged leptons mass generated by usual Higgs field)

$$m \sim U(\theta)^T \langle \Phi \rangle U(\theta)$$

$\langle \Phi \rangle = \text{diag}(\Phi_{11}, \Phi_{22}, \Phi_{33})$, $U(\theta)$ - mixing matrix

$T < \Lambda_G$ Relic neutrinos form bound states $\phi = (\nu_\alpha^T \nu_\beta)$
decay and annihilate into ϕ (neutrinoless Universe)

Symmetry of system, $SU(3)\times U(1)$, spontaneously broken by neutrino condensate - ϕ are goldstone bosons

ϕ get small masses due explicit symmetry breaking by WI via loops

Mixing and topological defects

G.Dvali , L Funcke,
T Vachaspati
2112.02107 [hep-ph]

Symmetry breaking: $SU(3) \rightarrow Z_2 \times Z_2 \rightarrow I$ ⇒ string-wall network

Length scale of strings ~ inter-string separation

$$\xi = 10^{14}\ \mathrm{m}\ (\lambda/a_G)\left(\frac{\Lambda_G}{1\ \mathrm{meV}}\right)^{7/2}$$

⬆

(self-coupling of string field Φ/scale factor of phase transition)

Travelling around string winds VEV $\langle\Phi\rangle$ by the SU(3) transformation:

$$\langle \Phi\ (\theta_S) \rangle = \omega(\theta_W)^T \langle\Phi\rangle\, \omega(\theta_W)$$

$\omega(\theta_W)$ path - O(3) transformation with angles $\theta_W = (\theta_W^{12}, \theta_W^{13}, \theta_W^{23})$.

After the path ω mixing changes as $U = U(\theta)\, \omega(\theta_W)$

over length ξ: $\theta_W = O(1)$

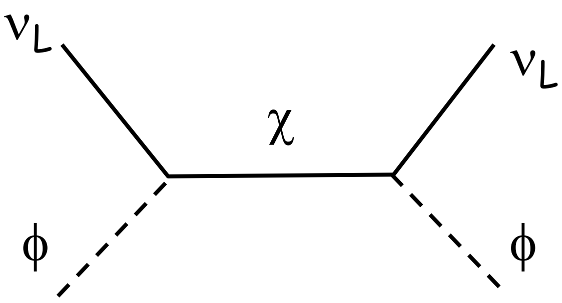
Solar system moves through frozen string-DW background with $v = 230$ km/sec. For 6 years (operation of Daya Bay) $d = vt = 4 \times 10^{13}$ m - comparable with expected ξ

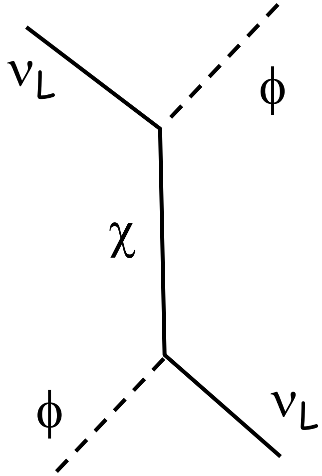
VEV or refraction on scalar DM?

S. F Ge and H Murayama, 1904.02518 [hep-ph]
Ki-Yong Choi, Eung Jin Chun, Jongkuk Kim, 1909.10478 [hep-ph]
2012.09474 [hep-ph]

Elastic forward scattering of ν on background scalars ϕ with fermionic χ mediator:

$L = g\,\overline{\nu_L}\,\chi\,\phi + \text{h.c.}, \quad g < 10^{-7}$





Resonance: $s = m_\chi^2$

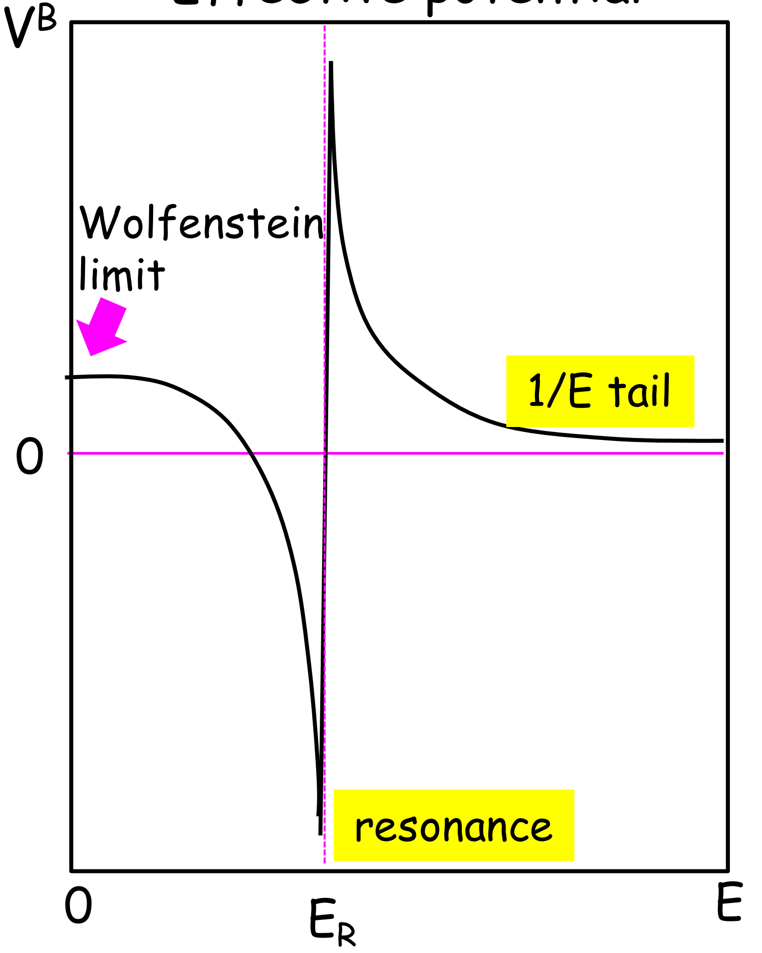
For ϕ at rest the resonance ν energy:

$$E_R = \frac{m_\chi^2}{2m_\phi}$$

For small m_ϕ resonance at low, observable energies

A.Y.S. , V. Valera, 2106.13829 [hep-ph]

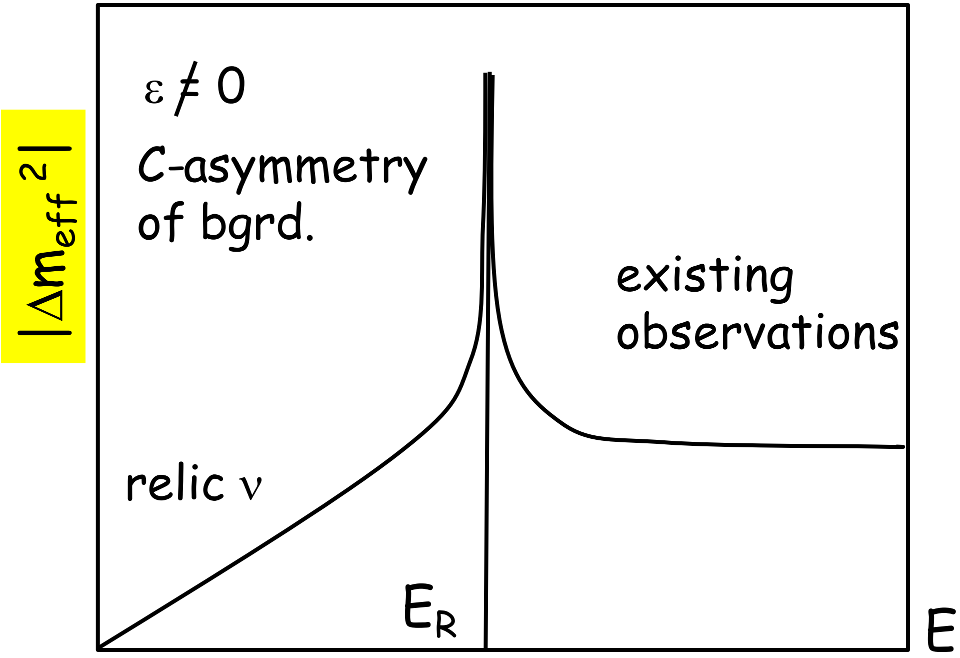
Effective potential



Effective Δm^2

$$\Delta m_{eff}^2 \sim \frac{y^2 n_\phi}{4\, m_\chi} \begin{cases} 1, & E \gg E_R \\ \varepsilon \dfrac{E}{E_R}, & E \ll E_R \end{cases}$$

$\Delta m_{eff}^2 \sim 2EV^B$



Δm_{eff}^2 = constant - checked down to 0.1 MeV

→ take $E_R \ll 0.1$ MeV

For $E_R = 0.01$ MeV:

KATRIN, E ~ 1 eV: $m_{eff} < 2\ 10^{-4}$ eV - undetectable

A.Y.S. ...

COSMOLOGY

$m_{eff}^2 \sim n_\phi \sim (1 + z)^3$ → increased in the past while VEV = const

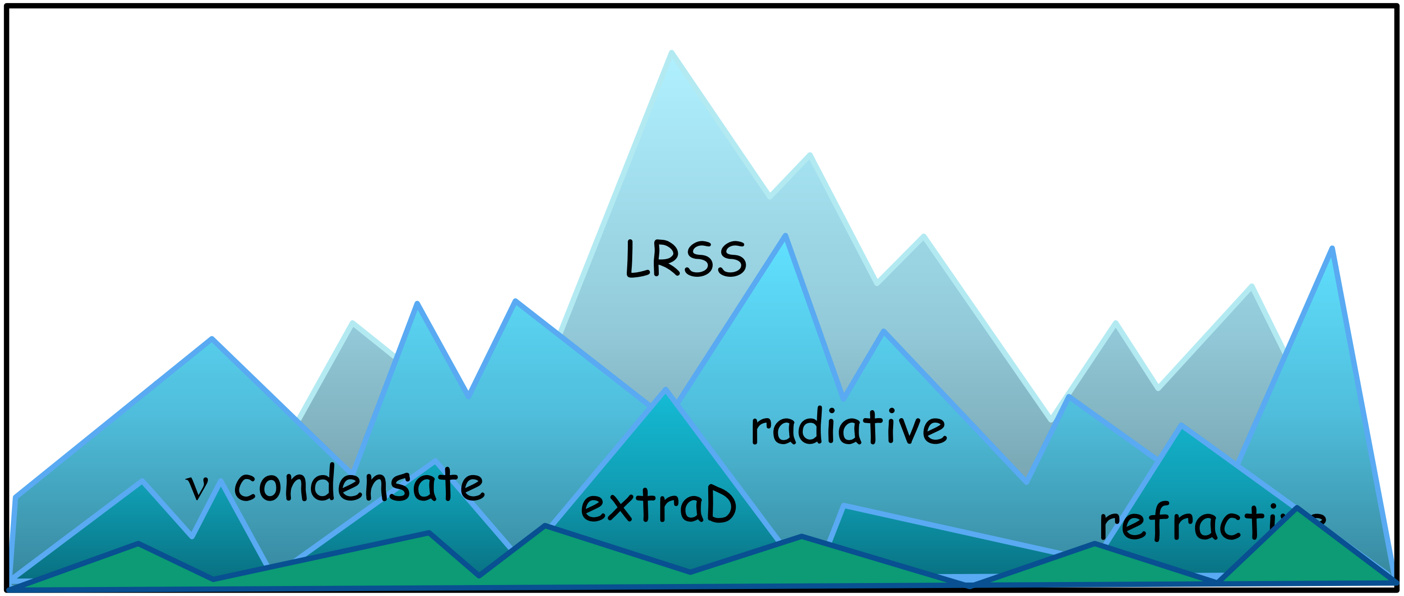
Relic ν, $E = 10^{-4}$ eV: $m_{eff}(0) < 5\ 10^{-6}$ eV: $m_{eff}(z = 1000) \sim 0.15$ eV,

no problem

$\Delta m^2 = 0$ in vacuum?

Summary

Rabi’s scenarios of neutrino mass alive and flourishing



Backup

L and B-L

R.N. Mohapatra and R.E. Marshak
PRL 44, 20 (1980) 1316

In L-R U(1) can be interpreted as

$U(1)_{L+R} = U(1)_{B-L}$

Quark-lepton correspondence

$SU(2)_L \times SU(2)_R \times SU(4)$

$SU(3)_c \times U(1)_{B-L}$ → unification of color and B-L

The same symmetry breaking

$\Delta L = 2$ effects

Majorana neutrino mass
$\beta\beta_{0\nu}$ - decay

$\Delta B = 2$ effects

$n - \bar{n}$ oscillations

Rates close to experimental bounds for $\langle \Delta_R \rangle \sim 10^4$ GeV

Features

Neutrino masses from the Double seesaw with

$M_S \sim M_{PL}$, $M_D \sim \langle 16_H \rangle \sim M_{GUT}$ $m_D, M_D = \text{diag}$

$\delta_{CP} = 144 - 210^0$ (NO)

Similar non-SUSY structure with 10_H, 16_H, 45_H (responsible for gauge symmetry breaking)

A. Preda, G. Senjanovic, M. Zantedeschi, 2201.02785[hep-ph]

High dimensional operators, correspond to the integrated out Dark sector but with $\Lambda \sim 10\ M_{GUT}$, $M_{GUT} \sim 4\ 10^{15}$ GeV

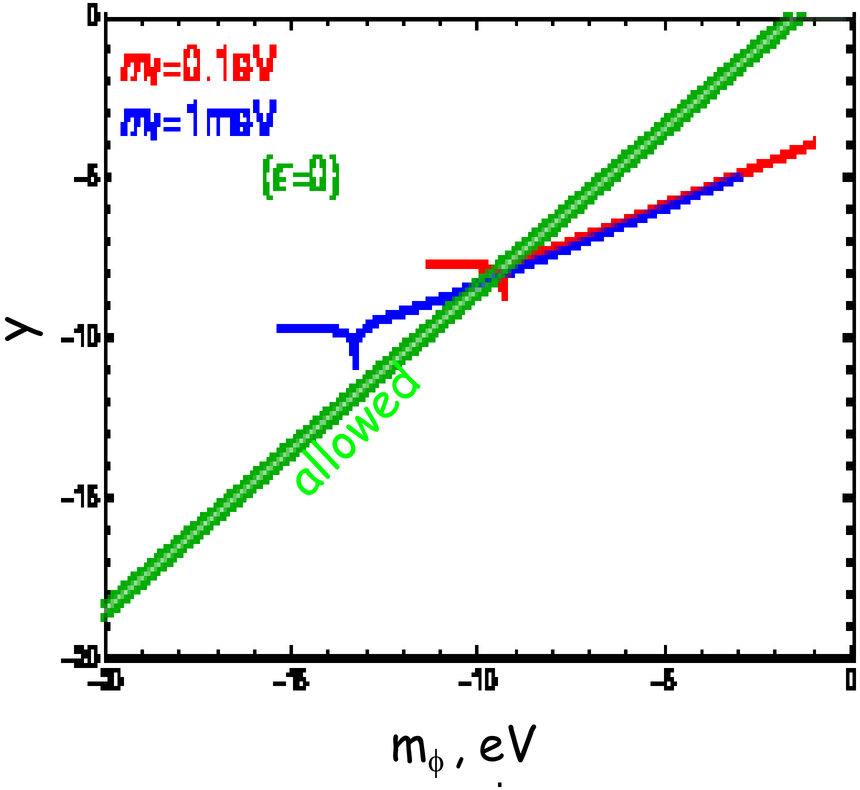
$M_D \sim \langle 16_H \rangle \sim M_I \sim 5\ 10^{14}$ GeV

Unification is achieved by strong mass splitting in 45_H with weak tripled and color octet, as well as in 10_H with scalar quark doublet having masses below 10 TeV

accessible to LHC ?

Bounds on parameters

Ki-Young Choi, Eung Jin Chun, Jongkuk Kim, 2012.09474 [hep-ph]



Green band: $\Delta m_{eff}^2 = \Delta m_{atm}^2$

Upper bounds on y from scattering of neutrinos from SN1987A on DM ϕ with zero C- asymmetry and two different masses of mediator f

Similar bound from Lyα (relic neutrinos) .

Allowed values:

$m_f < 10^{-3}$ eV
$m_\phi < 10^{-10}$ eV
$y < 10^{-9}$

the corresponding resonance energy $E_R = 0.01$ MeV

Cosmological bound is satisfied

Summary

Rabi's scenarios of neutrino mass alive and flourishing

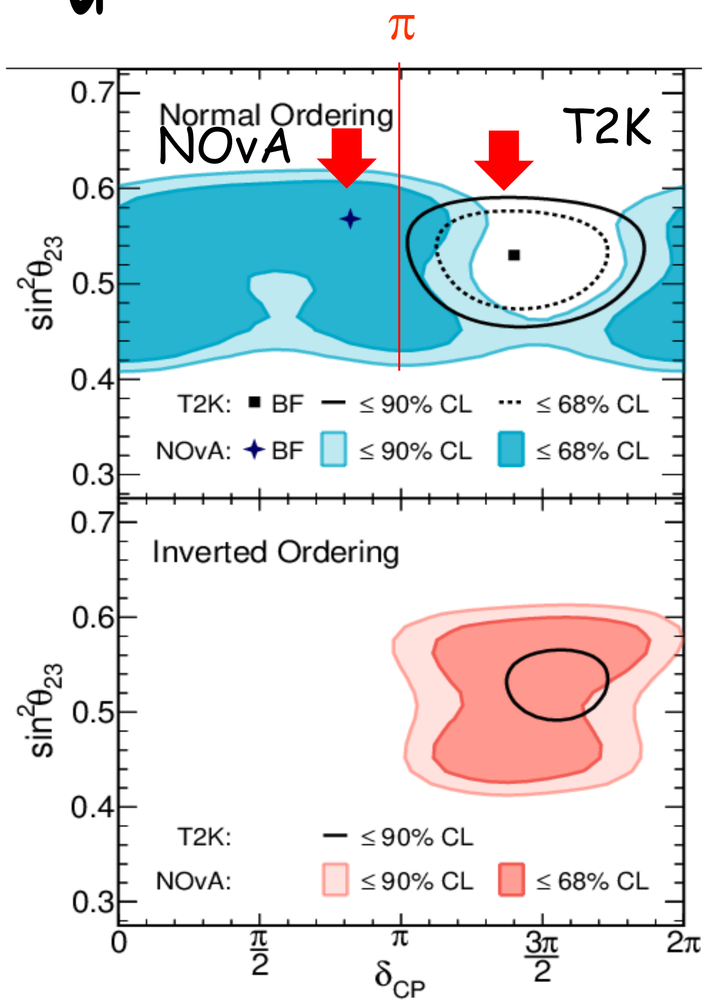
Practically nothing is excluded yet, although crucial tests can be around the corner

Any new observation can affect the picture

Gallium anomaly, BEST, LSND/MB: light sterile neutrinos representatives of light dark sector?

Neutrino interactions with light dark sector, resonance refraction at low energies, medium induced neutrino mass

δ_{CP} : NOvA - T2K tension?



No tension in the case of inverted ordering

2108.08219 [hep-ex]

NOvA: $\delta_{CP} = 0.82\pi$, disfavors $\delta_{CP} = 1.5\pi$ by 2σ

NOvA-T2K difference can be related to different baselines and matter effects

Reconcile with NSI

Sterile neutrinos do not help?

S. Chatterje, A. Palazzo, 2008.04161 [hep-ph], 2005.103338 [hep-ph]

Statistical fluctuations/systematics?

Global fit: $\delta_{CP} \rightarrow \pi$

Effective neutrino mass and cosmology

★ Due to dependence on energy and number density of scatterers m_{eff} can be different in different space-time points

★ Red shift dependence

$m_{eff}(z) \sim \sqrt{n(z)}$ $n(z) = n_0 (1 + z)^3$

- effective mass increased in the past in contrast to standard mass generated by coupling with VEV (does not depend on z).

★ $m_{eff}(z) \sim [\xi (1 + z)^3]^{1/2} m_{eff}(loc)$

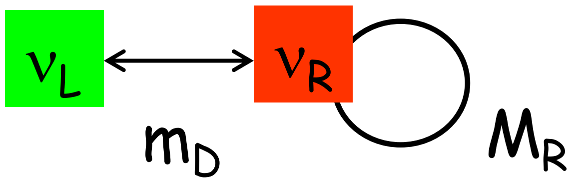
$1/\xi \sim 10^5$ - local (near the Earth) over-density of the background.

★ For $m_{eff}(loc) = 5\ 10^{-6}$ eV: $m_{eff}(1000) \sim 5\ 10^{-4}$ eV, and
$m_{eff}(10^5) \sim 0.5$ eV

Bound on sum of neutrino masses from structure formation is satisfied
m_{eff} dependence on E for not very small E_R resolve the problem

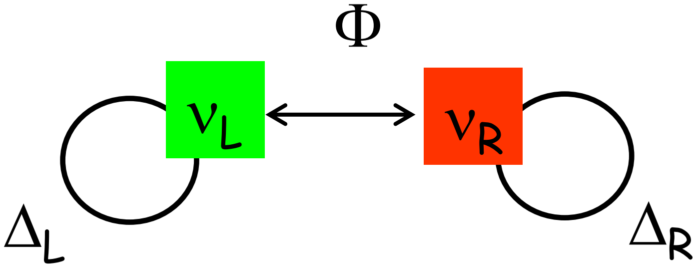
See-saw and L-R

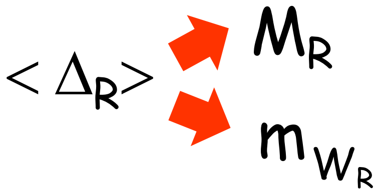
LSND



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

Historically:
getting neutrino
mass in LR





Seesaw scale is determined by the scale of L- R symmetry violation

$< \Delta_L > \neq 0$ → type II

Type I + II

LHC-filic scenarios

$\Delta m_{41}^2 = 1 - 2\ \mathrm{eV}^2$

Small neutrino mass with small masses of RH neutrinos

J Kersten, AYS, Phys.Rev.D 76 (2007) 073005, 0705.3221 [hep-ph]

Inverse seesaw

Low scale seesaw, a la νMSM

Bounds on the eV sterile neutrinos

BEST, reactors,
LSND/MB

$$\begin{pmatrix} m_{ee}^0 & \dots & m_{es}^0 \\ \dots & \dots & \dots \\ m_{es}^0 & \dots & m_{ss}^0 \end{pmatrix}$$

m_{ee}^0 should be large enough to cancel large induced mass $(m_{ee}^0)^2 / m_{ss}^0 \sim \sin^2 \theta_{41} m_4$

After decoupling of sterile neutrino:

$$m_{ee} = m_{ee}^0 - \tfrac{1}{4} \sin^2 2\theta_{41} \sqrt{\Delta m_{41}^2}$$

oscillations of active neutrinos, Cosmology

$\beta\beta_{0\nu}$ - decay

sterile neutrino

$$\boxed{\Delta m_{41}^2 < \frac{16(m_{ee}^0 - m_{ee})^2}{\sin^4 2\theta_{41}}}$$

$m_{ee}^0 < 0.156$ eV (90% C.L.)

KamLAND-Zen , S. Abe et al. 2203.02139 [hep-ex]

$\sin^2 2\theta_{41} = 0.4$

For NH: $m_{ee} \sim m_2 \sin^2 \theta_{21} = 2.5\ 10^{-3}$ eV $\quad \Delta m_{41}^2 < 2.4\ \text{eV}^2$

For quasi-degenerate: $m_{ee} < 0.03$ eV $\quad \Delta m_{41}^2 < 1.6\ \text{eV}^2$

disfavour
BEST,
Neutrino-4