Origins of Neutrino Mass

A. Yu. Smirnov

International Centre for Theoretical Physics, Trieste, Italy

Gif 2011, School on Neutrinos

Origins of neutrino mass are not known yet

We even don't know

- nature of neutrino mass:
  Dirac vs. Majorana,
  soft vs. hard;
- absolute mass scale and mass hierarchy
- number of neutrinos, etc..

plenthora of

What do we have is

ideas
conjectures
proposals
approaches
scenarios
mechanisms
models

which mutually exclude
each other and can not
be realized simultaneously

most of them are misleading

comments

Really we don't know the origins of neutrino mass
(in fact, we do not know yet origins of the electron mass)

We can speak about SEVERAL POSSIBLE origins of neutrino mass, and maybe no one of them is true

Neutrino mass should be considered in general context of all fermion masses

In this connection we can enquire about

ORIGINS of SMALLNESS of neutrino mass compared to masses of charged leptons and quarks

ORIGINS of DIFFERENCE between the mixing patterns of leptons and quarks.

Key points

1. Origins of neutrino mass and masses of other fermions should be considered simultaneously

m_l

m_ν

m_q

2. There is some form of quark-lepton unification, correspondence

leptons $\Leftrightarrow$ quarks

3. Masses (mass ratios) and mixing parameters are related

Some important elements can be still missed

Content

What are solid statements?

I. Neutrino mass & mixing:

II. Origins of mass: mechanisms and physics BSM

III. Neutrino mass and flavor symmetries

IV. New neutrino states

I. Neutrino mass & mixing

Generalities, various aspects

Solar neutrinos

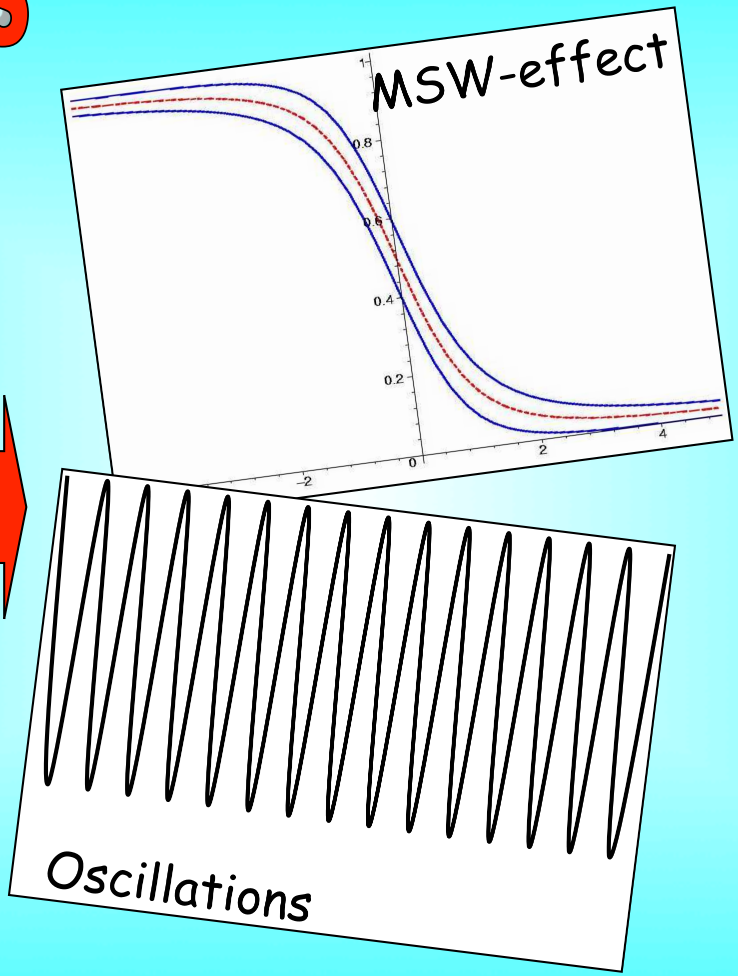
KamLAND

Atmospheric neutrinos

MINOS

K2K

T2K



$$\Delta m^2$$

$$\theta$$

$\Delta m^2 = m^2_i - m^2_j$

$m^2 = m\, m^+$

Dirac mass terms

and its properties

$\mathcal{L} = \ldots \; - m_D \, \overline{\nu_L} \, \nu_R + h.c.$

4 component → Dirac equation

connects left and right

Electroweak properties: $(I, \; I_3, \; Y) = (\frac{1}{2}, \; \frac{1}{2}, \; 1)$

electroweak symmetry is broken

Invariant under simultaneous transformation

$\nu_L \rightarrow e^{i\alpha}$

$\nu_R \rightarrow e^{i\alpha} \, \nu_R$

U(1) symmetry

interpretation – lepton number

Chiral symmetry is broken

ν_L and ν_R can not transform independently

$\nu_L \rightarrow e^{i\alpha} \, \nu_L \quad \nu_R \rightarrow e^{i\beta} \nu_R$

In the limit $m_D \rightarrow 0$ the chiral symmetry is restored → smallness of neutrino mass is ``technically natural'' (protected by chiral symmetry)

Majorana mass term

$\nu_R \rightarrow \nu_L{}^C$ charge conjugation: $\nu_L{}^C = C\,(\overline{\nu_L})^T \quad C = i\gamma_0\,\gamma_2$

$\mathcal{L} = \ldots - \frac{1}{2}\, m_L\, \nu_L{}^T C \nu_L + h.c.$ $\rightarrow$ two component massive neutrino

Electroweak properties $(I,\ I_3,\ Y) = (1,\ 1,\ 2)$ $(1, -1, -2)$ for h.c.

Not invariant under $\nu_L \rightarrow e^{i\alpha}\,\nu_L$

Lepton number of the mass operator: L = 2 and -2 (for h.c.)

mass term violates lepton number by $|\Delta L| = 2$

Processes with lepton number violation by $|\Delta L| = 2$ with probabilities $\Gamma \sim m_L{}^2$

$\beta\beta_{0\nu}$

Majorana neutrino

$$\nu_M^C = \nu_M$$

truly neutral
particle = antiparticle

In general:

$$\nu_M^C = e^{i\alpha}\,\nu_M$$

In terms of chiral components:

$$\nu_M = \nu_L + e^{-i\alpha}\,\nu_L^C$$

α is the Majorana phase

$$\mathcal{L} = \ldots - \tfrac{1}{2}\, m_M\, \overline{\nu}_M\, \nu_M = \tfrac{1}{2}\, m_M\, e^{i\alpha}\, \nu_L^T\, C\, \nu_L + \text{h.c.}$$

the same what we had before

The Majorana phase can be attached to the mass

Majorana phase does enter dispersion relation → oscillations

Dirac + Majorana

If right components exist, one can introduce also the Majorana mass terms

$$\mathcal{L} = \ldots - \tfrac{1}{2} M_R \, \nu_R^T C \nu_R + h.c.$$

$(I,\ I_3,\ Y) = (0, 0, 0)$ → mass term does not violate the EW symmetry

Still $|\Delta L| = 2$

If both LH and RH components exist the mass terms can be written in the basis (ν_L, N_L) $N_L = \nu_R^c$

$$\begin{pmatrix} m_L & m_D \\ m_D^T & M_R \end{pmatrix} \begin{matrix} \nu_L \\ N_L \end{matrix}$$

Different limits:

$\boxed{m_L = M_R = 0}$ – Dirac neutrino = two Majorana neutrinos with equal but opposite sign masses

$\boxed{m_L = M_R \ll m_D}$ – pseudo Dirac neutrino

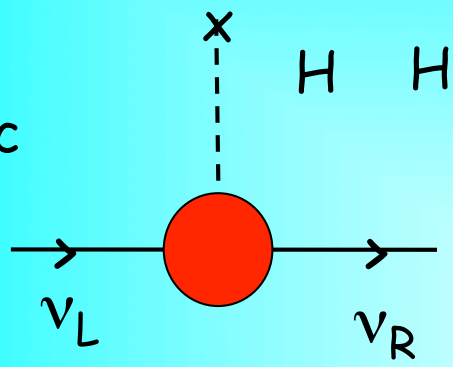
$\boxed{M_R \gg m_D}$ – seesaw limit

``Schizophrenic'' neutrinos…

R. Mohapatra

Neutrino mass and EW Symmetry breaking

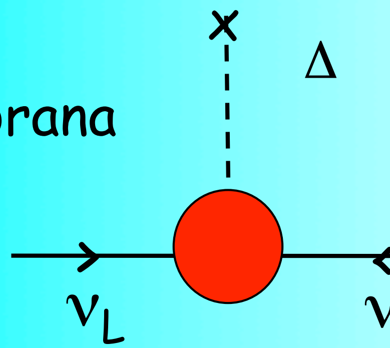
Dirac



Higgs doublet

$m_D = h \langle H \rangle$

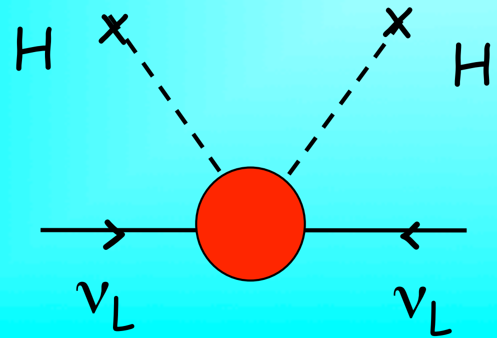
Majorana



Higgs triplet

$m_L = f \langle \Delta \rangle$

Elementary or composite operator which has $I_W = 1$



$m_L = f \langle H\, H \rangle$

Nature of neutrino mass

Smallness may indicate that nature of the neutrino mass (or at least what we observe in oscillations) differs from masses of other fermions

Is it of the same nature as the mass of electron or top quark?

Oscillations probe dispersion relation

$$E = E(p) \sim p + \frac{m\, m^{+}}{2p} + \sqrt{2}\, G_F\, n + V_{BSM} + \ldots$$

usual matter effect

Lorentz violation
CPT violation effect

Additional terms can be Expanded:

$$\delta E^2 + \zeta E^3 + \ldots$$

A. Kostelecky

$$\boxed{m_\nu(\text{oscillations}) = m_\nu(\text{kinematics})} \quad ?$$

Testing nature of mass

New contributions can be identified by measuring
the same Δm^2 and θ in experiments with different enviroment:

- in vacuum and in matter
- in magnetic fields
- at different energies
- for neutrinos and antineutrinos

LSND, MinoBooNE, MINOS ?

Hard vs. soft

In general: $\boxed{m_\nu = m_{standard} + m_{soft}(E,n)}$

medium (environment) dependent (``soft") component

In matter: $m_\nu{}^2 = m_{standard}{}^2 + 2VE$

Can m_{soft} dominate?

P. De Holanda $\boxed{m_i = m_0 \ \tanh(\lambda_i \, \rho(g/cm^3))}$

$m_0 = 5\ 10^{-2}$ eV $\quad \lambda_i = (\ 0, 0.06, 3)$

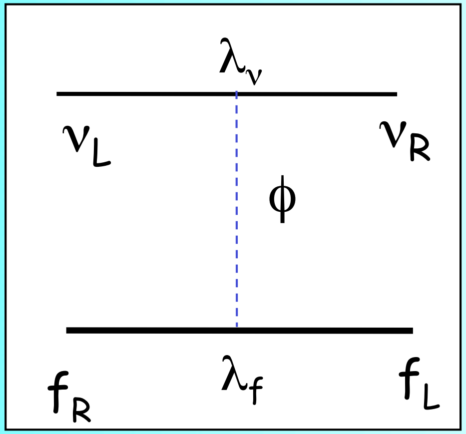
BOREXINO: absence of a significant Day-Night asymmetry for Be-neutrinos

G. Bellini, et al 1104.2150 [hep-x]

Excludes this possibility

"Soft" neutrino mass?

in the context of
MaVaN scenario



Exchange by
very light scalar

$m_\phi \sim 10^{-8} - 10^{-6}$ eV

$f = e, u, d, \nu$

D B Kalplan, E. Nelson,
N. Weiner , K. M. Zurek
M. Cirelli, M.C. Gonzalez-Garcia,
C. Pena-Garay
V. Barger, P Huber, D. Marfatia

chirality flip –
true mass:

$\boxed{m_{soft} = \lambda_\nu \lambda_f n_f / m_\phi}$

$\lambda_f \sim \phi / M_{Pl}$

In the evolution equation: $\boxed{m_{vac} \rightarrow m_{vac} + m_{soft}}$

generated by some short range
physics (interactions) EW scale VEV

medium and energy
dependent mass

Neutrino mixing

Flavor neutrino states:

ν_e ν_μ ν_τ

e μ τ

- correspond to certain charged leptons
- interact in pairs
- flavor –characteristic of interaction

$n \rightarrow p + e^- + \bar{\nu}_e$

$\pi \rightarrow \mu + \nu_\mu$

Mass eigenstates

ν_1 ν_2 ν_3

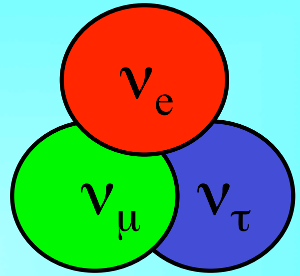
m_1 m_2 m_3

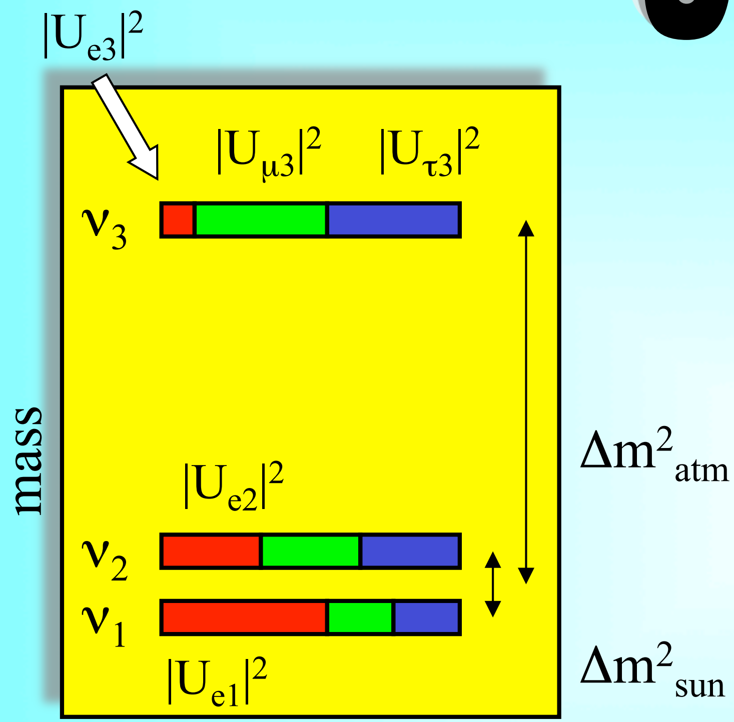
Mixing

Flavor states $\neq$ Mass eigenstates

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

Mixing angles





Normal mass hierarchy

$$\Delta m^2_{atm} = \Delta m^2_{32} = m^2_3 - m^2_2$$

$$\Delta m^2_{sun} = \Delta m^2_{21} = m^2_2 - m^2_1$$

Mixing parameters, parameterization

$$\tan^2\theta_{12} = |U_{e2}|^2 \;/\; |U_{e1}|^2$$

$$\sin^2\theta_{13} = |U_{e3}|^2$$

$$\tan^2\theta_{23} = |U_{\mu 3}|^2 \;/\; |U_{\tau 3}|^2$$

Rotation in 3D space

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

$$U_{PMNS} = U_{23}\; I_\delta\; U_{13}\; I_{-\delta}\; U_{12}$$

Mixing matrix

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

where $\nu_f = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$ $\quad \nu_{mass} = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

the matrix is unitary:

$$\boxed{U_{PMNS}^{+}\,U_{PMNS} = I}$$

Pontecorvo-Maki-Nakagawa-Sakata mixing matrix

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$U_{\alpha i} = |U_{\alpha i}|\, e^{i\phi_{\alpha i}}$$

Due to unitarity and possibility to renormalize wave functions of neutrinos and charge leptons only one phase is physical

Parameterization

$U_{PMNS} = U_{23}\ I_\delta\ U_{13}\ U_{12}$

$I_\delta = \mathrm{diag}\,(1,\ 1,\ e^{i\delta})$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}\,s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$c_{12} = \cos\theta_{12}$, etc.

δ is the Dirac CP violating phase

θ_{12} is the ``solar'' mixing angle

θ_{23} is the ``atmospheric'' mixing angle

θ_{13} is T2K angle

Mixing and mass matrices

Off-diagonal $M_l \neq M_\nu \Rightarrow$ $\nu_f = U_{PMNS} \nu_{mass}$

Diagonalization:

Mixing matrix

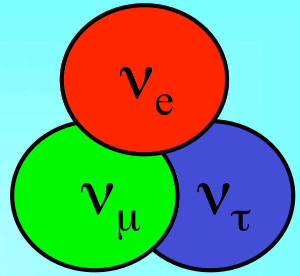
Mass hierarchy

$M_l = U_{lL} m_l^{diag} U_{lR}^+$ $M_\nu = U_{\nu L} m_\nu^{diag} U_{\nu L}^T$ for Majorana neutrinos

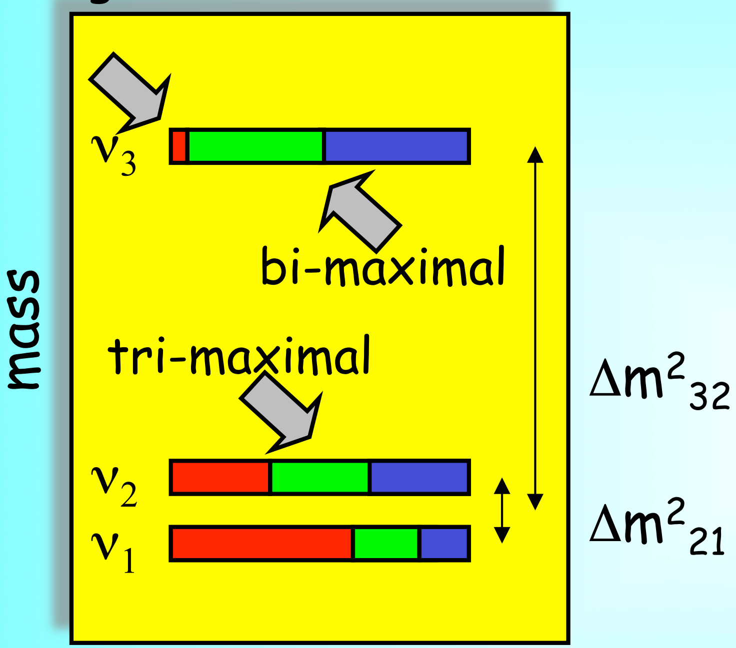
$U_{PMNS} = U_{\nu L} U_{lL}^+$ $m_\nu^{diag} = (m_1, m_2, m_3)$

Flavor basis: $M_l = m_l^{diag}$ $U_{PMNS} = U_{\nu L}$

Mixing

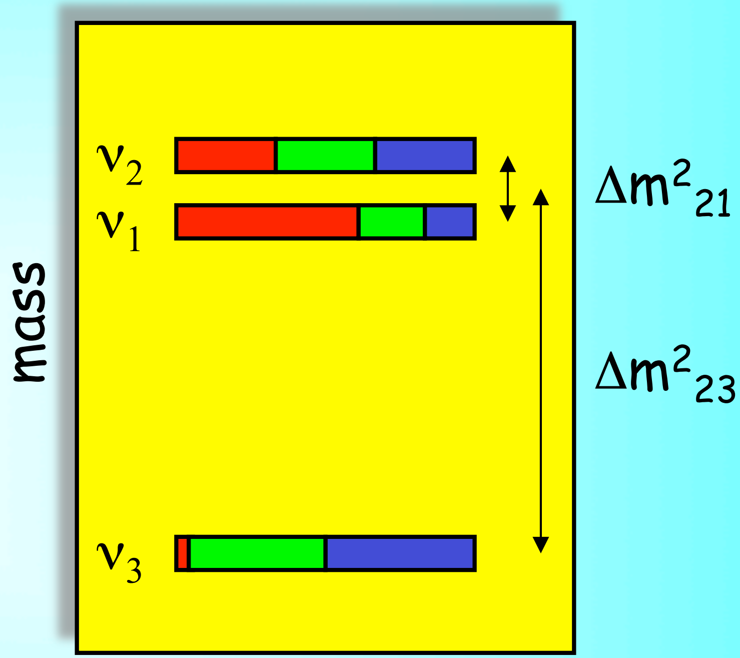


non zero
1-3 mixing



Normal mass hierarchy

?



Inverted mass hierarchy

Tri-bimaximal mixing
if 1-3 mixing is zero

Correct measure of mixing?

Salient features:

Small neutrino masses

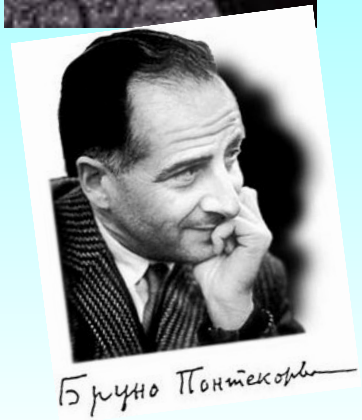
related?

pattern of mixing

New symmetries?

indicate that most probably
we are touching
something qualitatively new

Absolute mass scale



MINOS, atmospheric neutrinos

$m > \sqrt{\Delta m_{31}^2} > 0.045$ eV

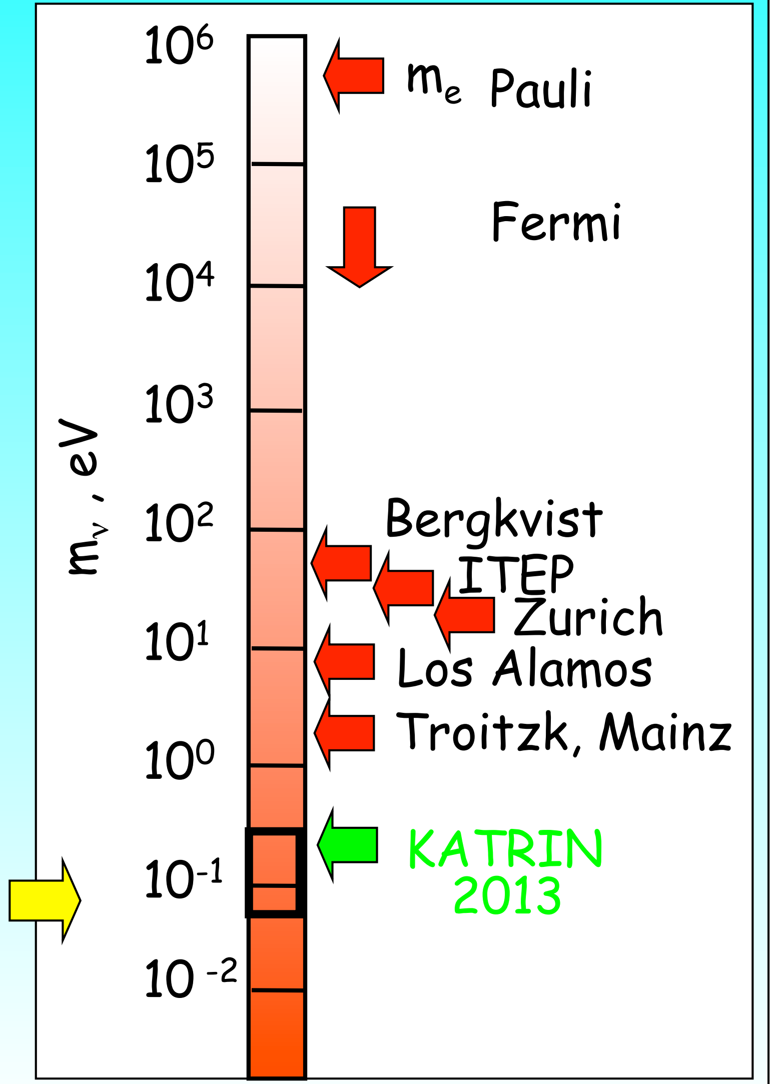
COSMOLOGY: bound on the sum of neutrino masses

$m < \Sigma/3 < 0.2 - 0.3$ eV

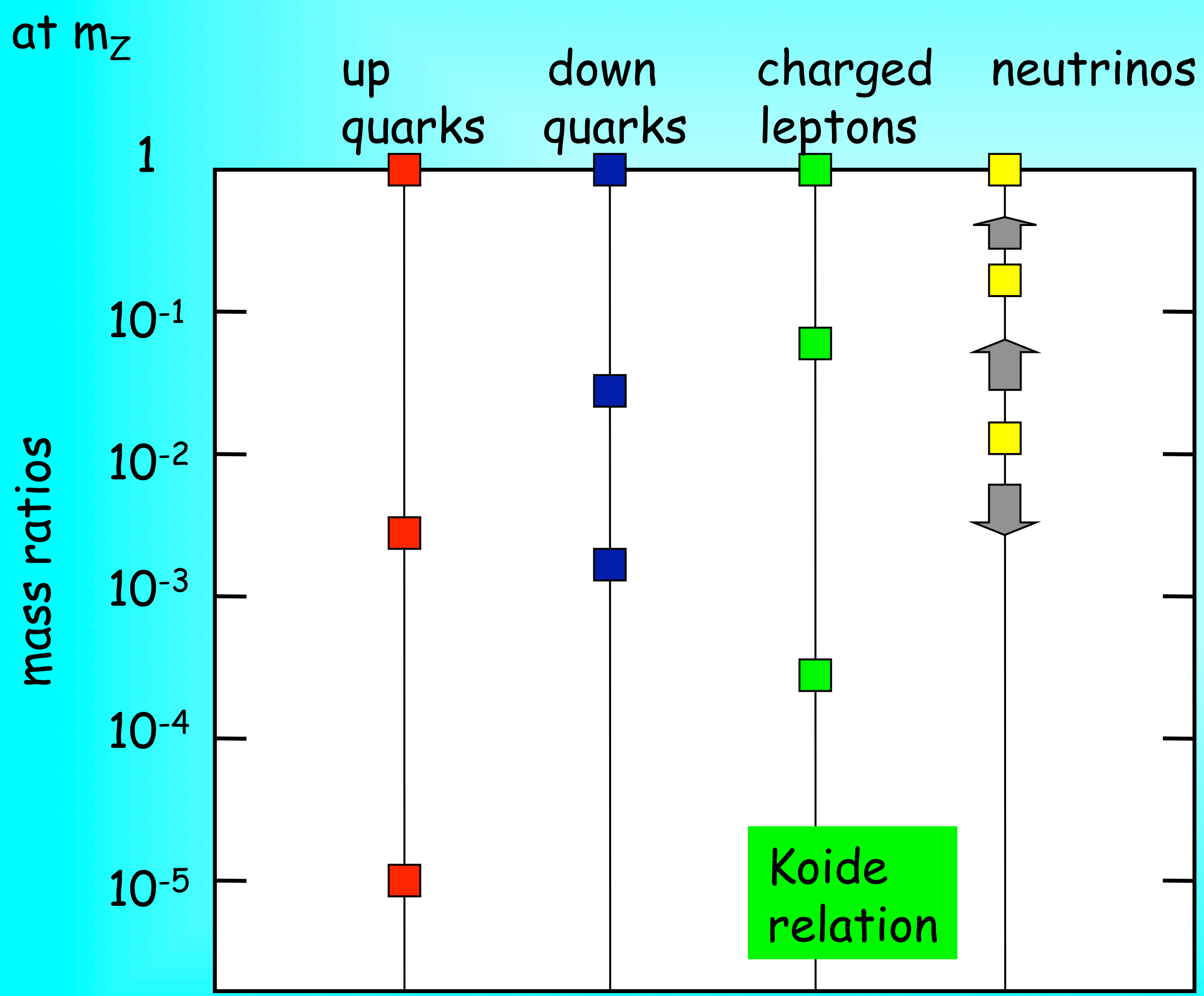
The heaviest neutrino has mass is in the range (0.045 - 0.30) eV

$m_\nu / m_\tau \sim 10^{-10}$

Kinematical measurements



Mass hierarchies



Solar, KamLAND

$$\frac{m_2}{m_3} \gtrsim \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}}$$

~ 0.18

Neutrinos have the weakest mass hierarchy (if any) among fermions

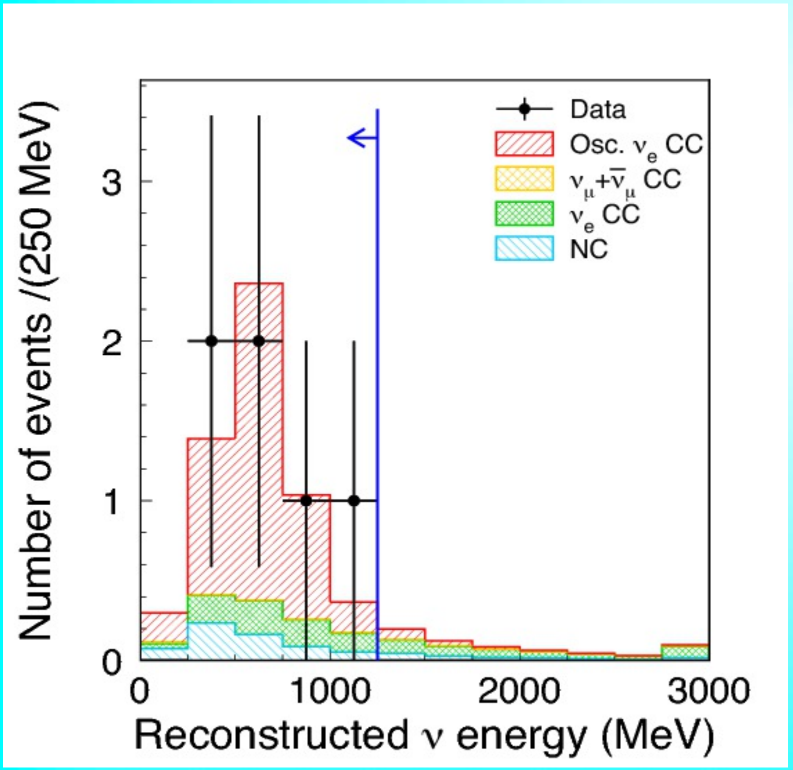
Related to the large lepton mixing?

$m_u \, m_t = m_c^2$

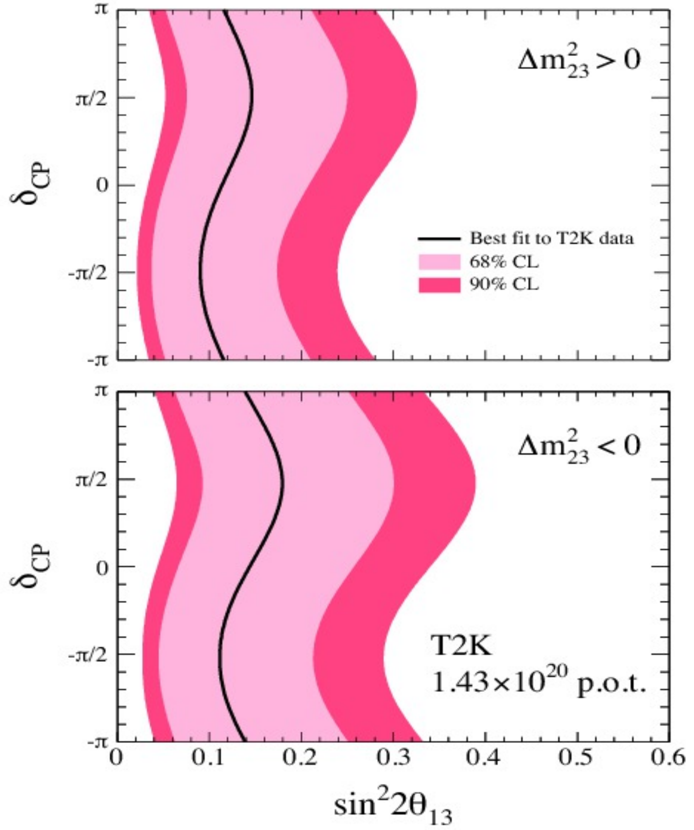
$\sin\theta_C \sim \sqrt{m_d/m_s}$ Gatto-Sartori-Tonin relation

T2K: 1-3 mixing

K Abe, et al [The T2K Collaboration] 1106.2822 [hep-ex]



for maximal 2-3 mixing



Background = 1.5+/-0.3

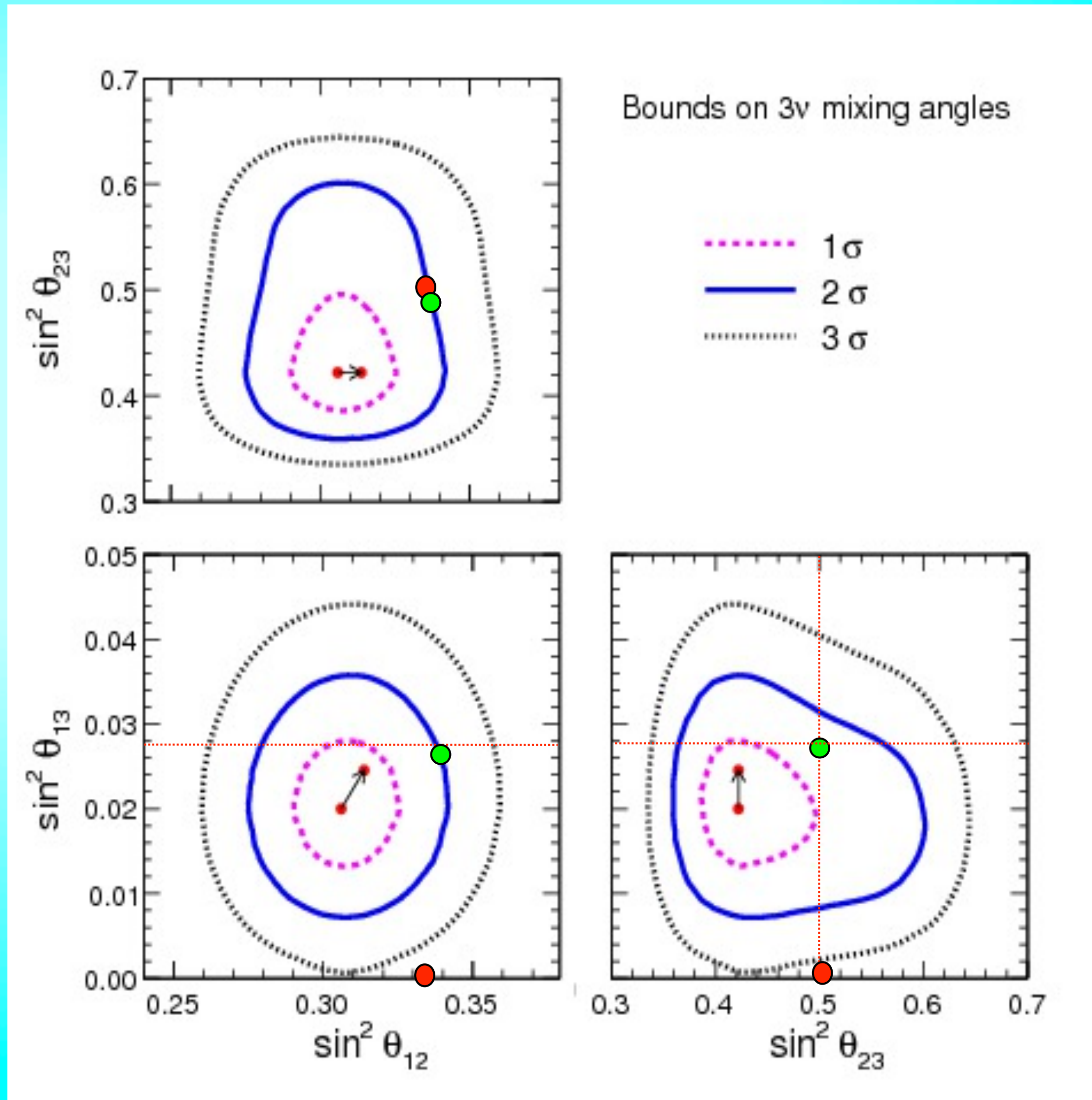
$\sin^2 2\theta_{13} \sim 0.11$

Global fit

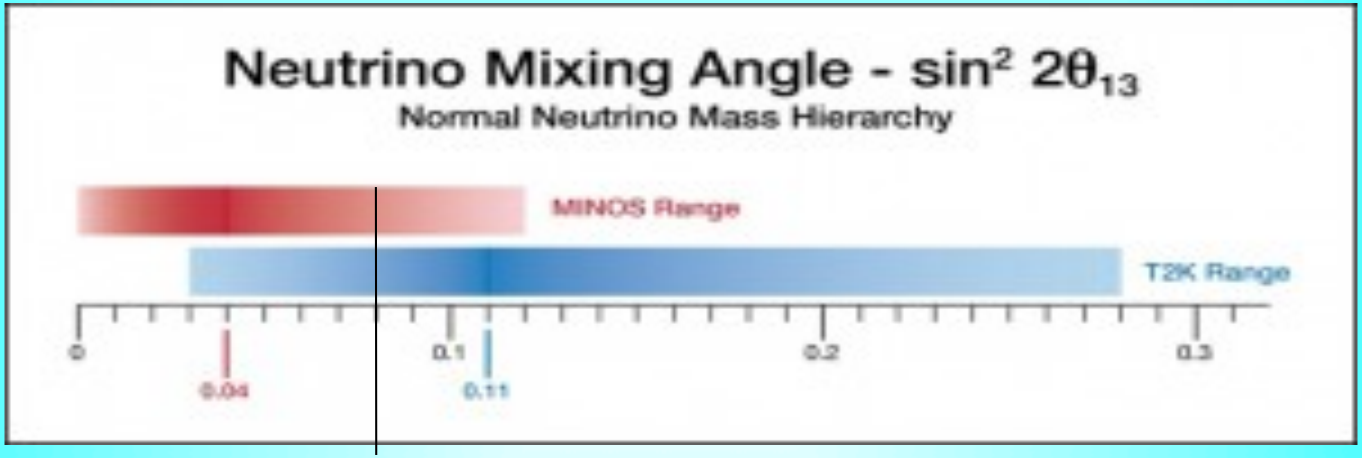
G.L Fogli et al., 1106.6028 [hep-ph]

- TBM
- QLC

New reactor fluxes
- shift by arrows



MINOS & T2K

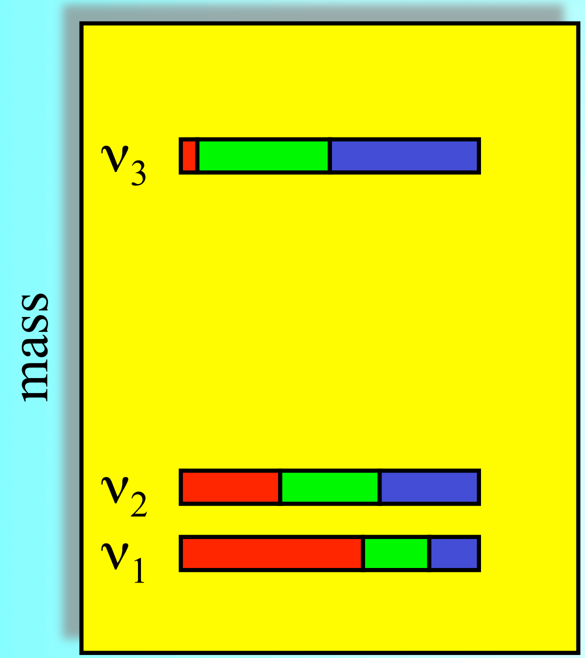


Global fit

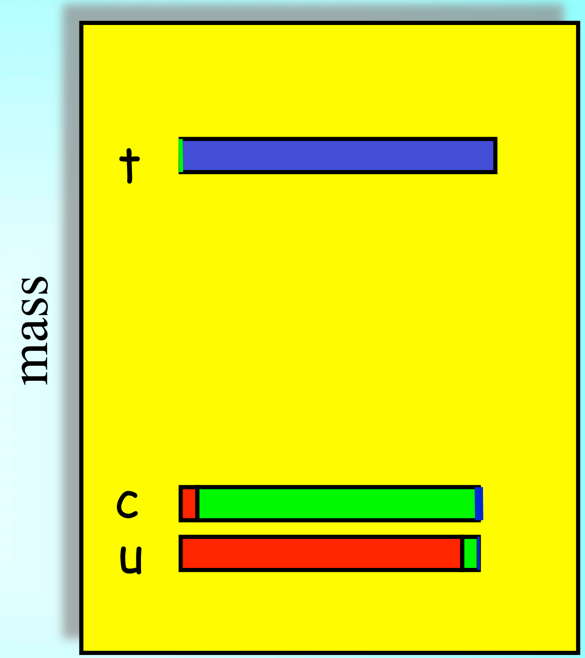
Typical for flavor models of TBM: $\sin\theta_{13} \sim \sin^2\theta_C$

Strongly broken TBM?

Leptons versus quarks



QLC



Leptons

Quarks

small mixing

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

$U_d = U_{CKM}^{+}\, U$ $U = (u, c, t)$

combination of down-quarks produced with a given up quark

II. Possible origins of neutrino mass

Two aspects:

Connecting mass hierarchy

Suppression of the Dirac mass of natural (EW) scale

Generation of small finite mass

Suppression:

- No right handed neutrinos
- Seesaw
- symmetry (unnatural to introduce for RH neutrinos)
- multi-singlet mechanisms

Seesaw mechanism do these two things simultaneously

No new symmetry is needed

Seesaw – only suppression,
e.g. if the RH masses are at Planck scale.
The dominant contribution - from another mechanism

Smallness of m_ν

New large mass scale

See-saw mechanism

Extra dimensions

Overlap mechanism

different localization

New symmetries

Forbid the usual Dirac mass terms

Radiative generation

High dimension operators

``Chiral mismatch"

Small VEV

Properties of RH neutrino components

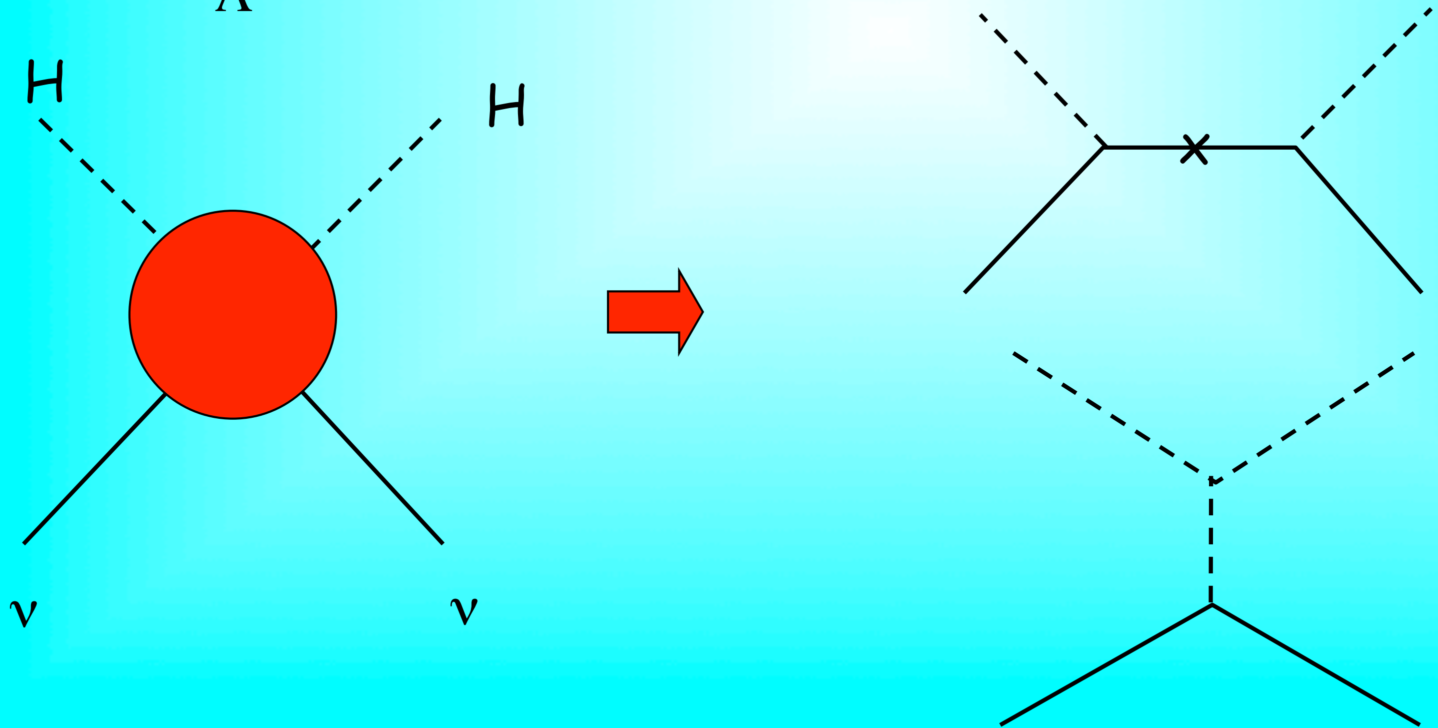
Connection to other hierarchies

D5 operator

S. Weinberg

If no new particles at the EW scale, after decoupling of heavy degrees of freedom → set of non-renormalizable operators

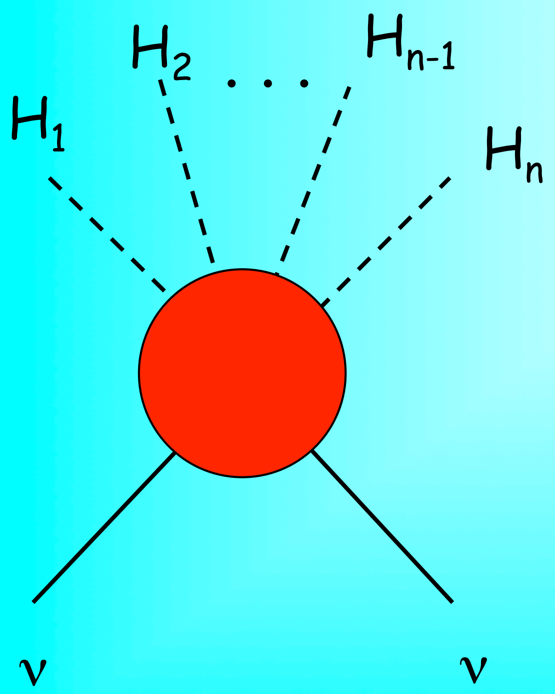
$$\frac{1}{\Lambda}\ L\,L\,H\,H$$



Higher dimension operator

D=5 operator can be suppressed by symmetry

$$H \rightarrow i\,H$$



$$\frac{1}{\Lambda^{n-1}}\ L\,L\,H^{\,n}$$

allows to reduce the scale of new physics responsible for neutrino mass generation

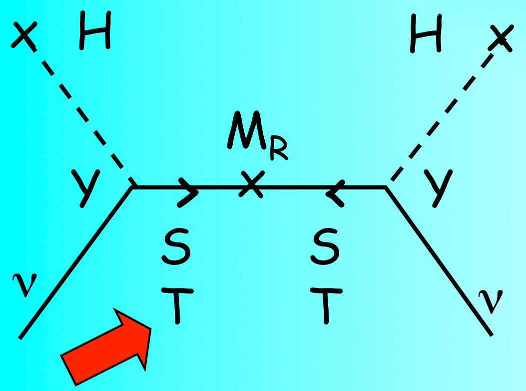
$$m_\nu = \frac{\langle H\rangle^{\,n}}{\Lambda^{n-1}}$$

$$m_\nu = \frac{1}{\Lambda^{n-1}}\ \Pi_{i\,=\,1\ldots n}\ \langle H_i\rangle$$

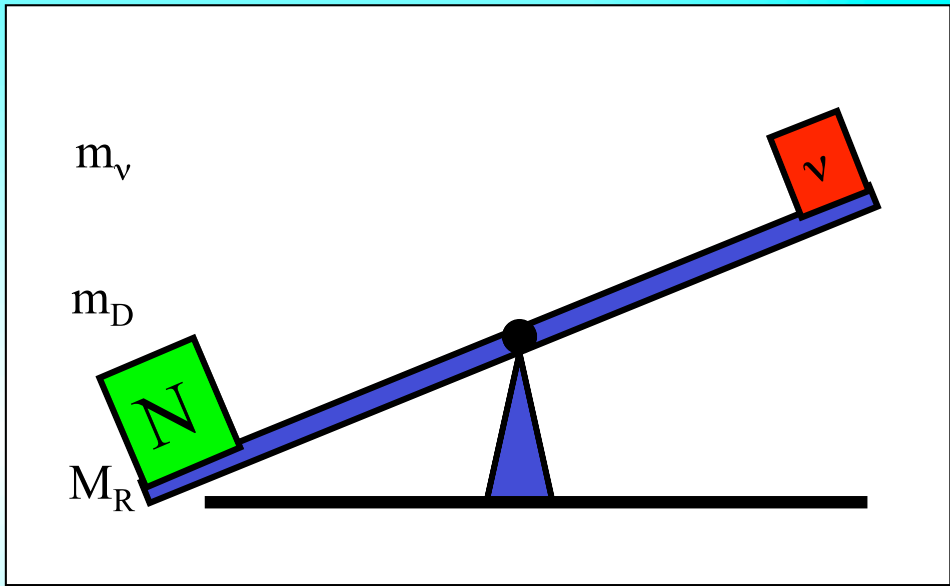
See-saw

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

Type 1



$m_D = Y\langle H\rangle$



Type 3 (SU(2) triplet intermediate state)

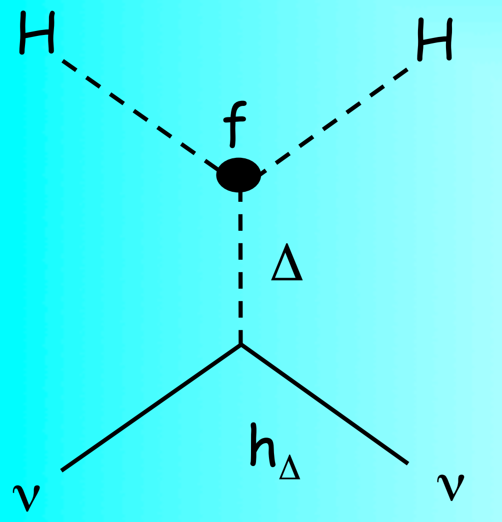
R Foot, H Lew, X G He, G C Joshi

Mass matrix:

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

if $M_R \gg m_D$ ⇒ $\boxed{m_n = -\ m_D^T\, M_R^{-1}\, m_D}$

See-saw type-II



M. Magg and C. Wetterich
G. Lazarides, Q Shafi and C Wetterich
R. Mohapatra, G. Senjanovic,

Seesaw for VEV's:

$$\langle \Delta \rangle = \langle H \rangle^2 f / M_\Delta^{\,2}$$

$$m_\nu = h_\Delta \langle \Delta \rangle = h\, f \langle H \rangle^2 / M_\Delta^{\,2}$$

Ligh triplet?

Double Seesaw

Three additional singlets S which couple with RH neutrinos

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

R.N. Mohapatra
J. Valle

Beyond SM:
many heavy singlets
...string theory

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

μ - scale of B-L violation

$\mu = 0$	massless neutrinos	violation of universality, unitarity
$\mu \ll M_D$	Inverse seesaw	allows to lower the scales of the neutrino mass generation
$\mu \gg M_D$	Cascade seesaw	explains intermediate scale for the RH neutrinos

$\mu \sim M_{Pl}$, $M \sim M_{GU}$ $\Rightarrow$ $M \sim M_{GU}^2/M_{Pl} \sim 10^{-14}$ GeV

Screening of Dirac structure

Quark-lepton symmetry $\quad m_D \sim m_q \quad$ - small mixing,
- strong mass hierarchy

Screening: $\quad$ if $m_D \sim M_D$

$m_\nu = A^2 \mu \qquad A \sim v_{EW}/M_{GU} \qquad M_S \sim \mu \sim M_{Pl}$

Structure of the neutrino mass matrix is determined by

M_S

origin of ``neutrino" symmetry

origin of maximal (or bi-maximal) mixing

leads to quasi-degenerate spectrum if e.g. $M_S \sim I$,

Q-l complementarity

Linear Seesaw

Three additional singlets S which couple both to the LH and RH neutrinos

$$\begin{pmatrix} 0 & m_D & m \\ m_D^T & 0 & M \\ m^T & M^T & 0 \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

$m \sim v_{EW}$

S. Barr

$$\boxed{m_\nu = m_D (M^T)^{-1} m^T + (\text{transponent})}$$

Linear in m_D

Cancellation of hierarchies for $M \sim m_D$

Heavy pseudo Dirac neutrino – resonance leptogenesis

Screening of the Dirac structure

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

$N \rightarrow l + H$

→ 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''

b - τ unification ⟺ large 2-3 leptonic mixing

Provide with all the ingredients necessary for seesaw mechanism

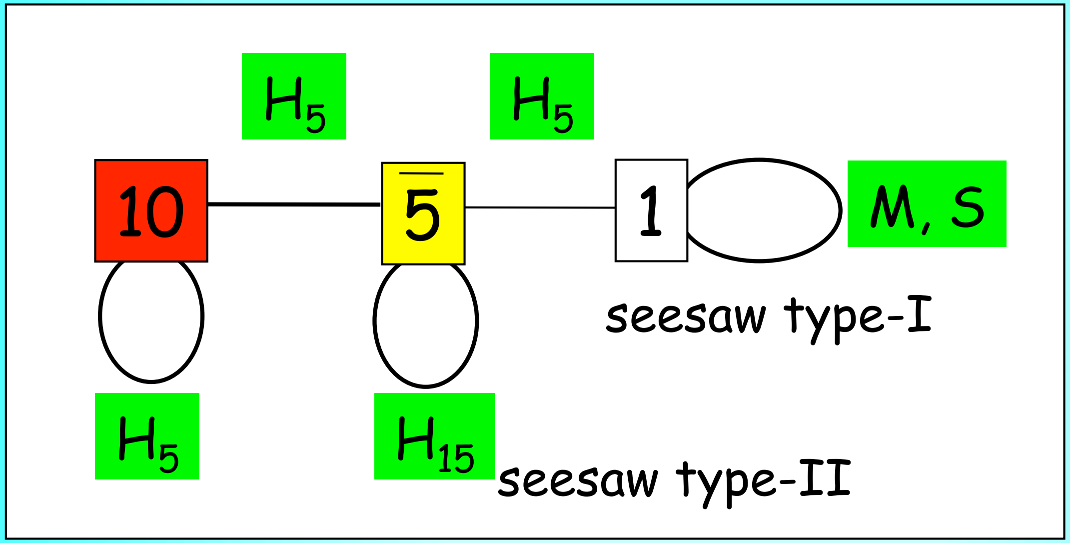
- RH neutrino components
- Large mass scale
- Lepton number violation

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

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

- charge quantization
- correct quantum numbers for all components

Gauge coupling unification
Proton decay?

SUSY without intermediate scales
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

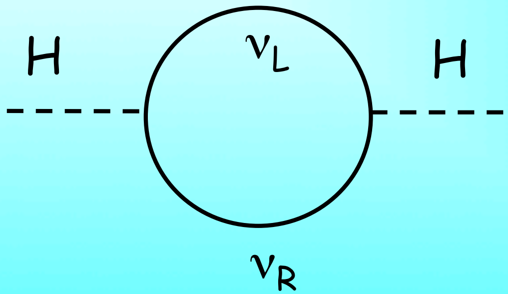
Neutrino interactions

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

L

R

BAU

Few 100 MeV
split ~ few kev

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

WDM

3- 10 kev

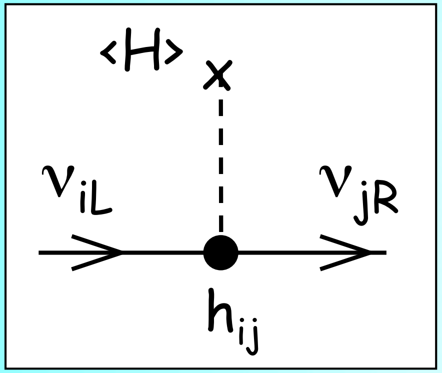
- warm dark matter
- radiative decays → X-rays

Normal
Mass
hierarchy

EW seesaw

Phenomenology of sterile neutrinos

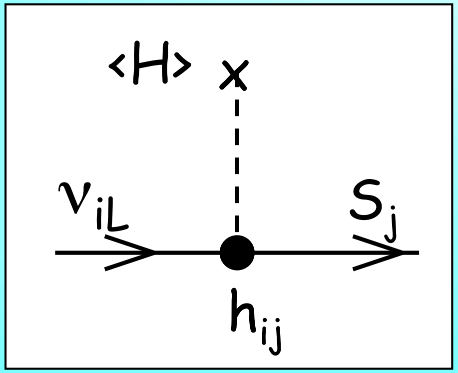
Small Yukawa couplings



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

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

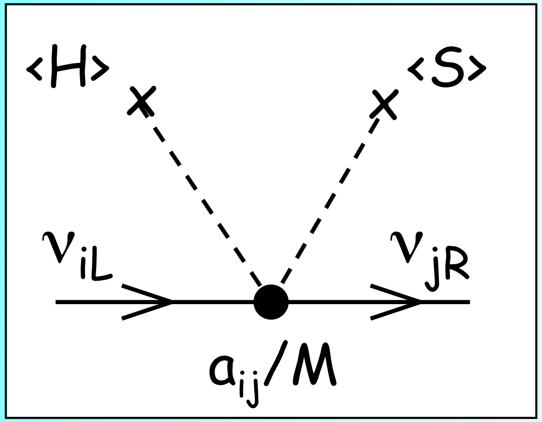
Suppressed by
symmetry or seesaw

Small effective couplings

renormalizable coupling is suppressed by symmetry

effective coupling produced by non-renormalizable operators:

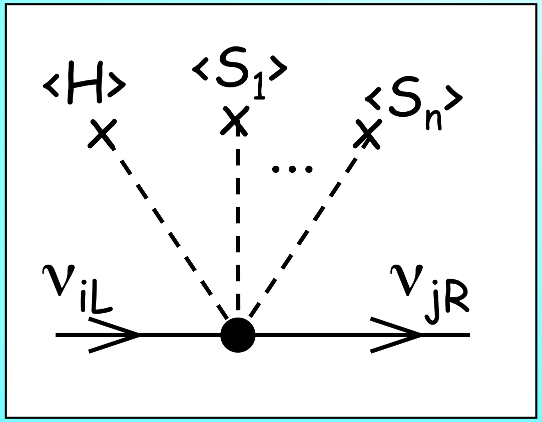
$$\boxed{a_{ij}\, l_{iL}\, \nu_{iL}\, H \frac{S}{M}}$$



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

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

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



in general

SUSY / GUT scales?

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

Relations and sum rules

``Minimal SO(10)'':
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 ...

Mass matrices

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

$$M_\nu = kY_{126}$$

assumption: Seesaw II gives main contribution

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

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

For second and third generation

$$M_\nu \sim M_l - M_d$$

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

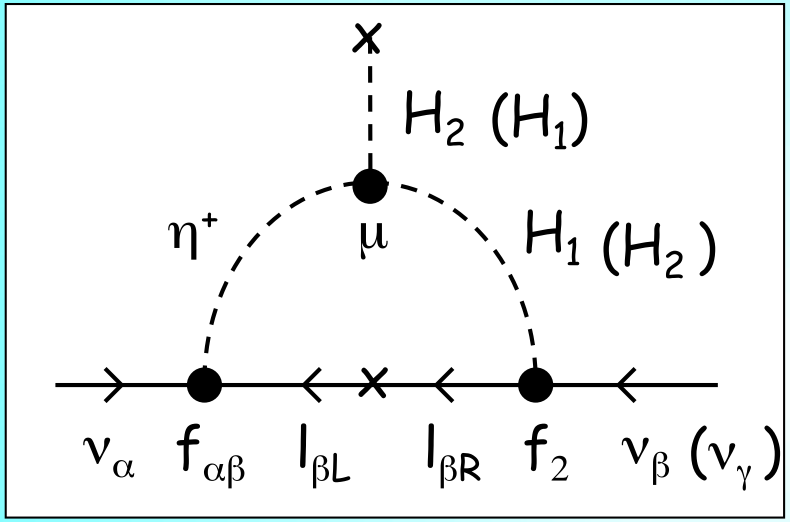
Large 2-3 mixing needs b - τ unification

S. Bertolini, et al

Zee-mechanism

No RH neutrinos

new bosons: singlet η^+, doublet H_2



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

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

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

X-G He

P. Frampton, M. C. Oh

T. Yoshikawa

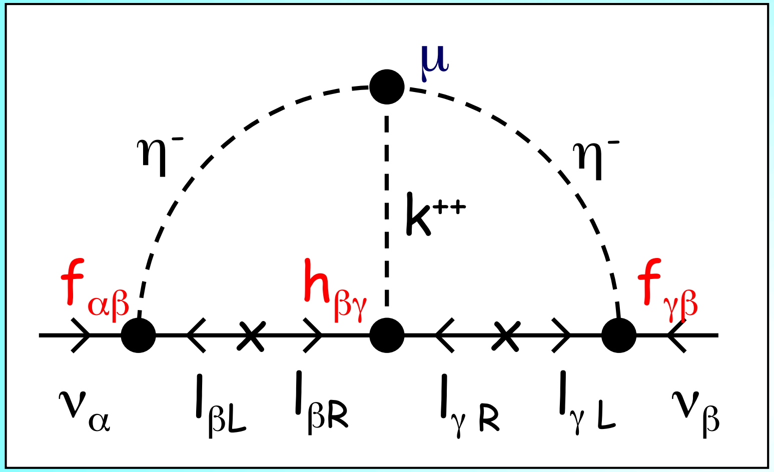
If only H_1 couples with leptons

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

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



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)

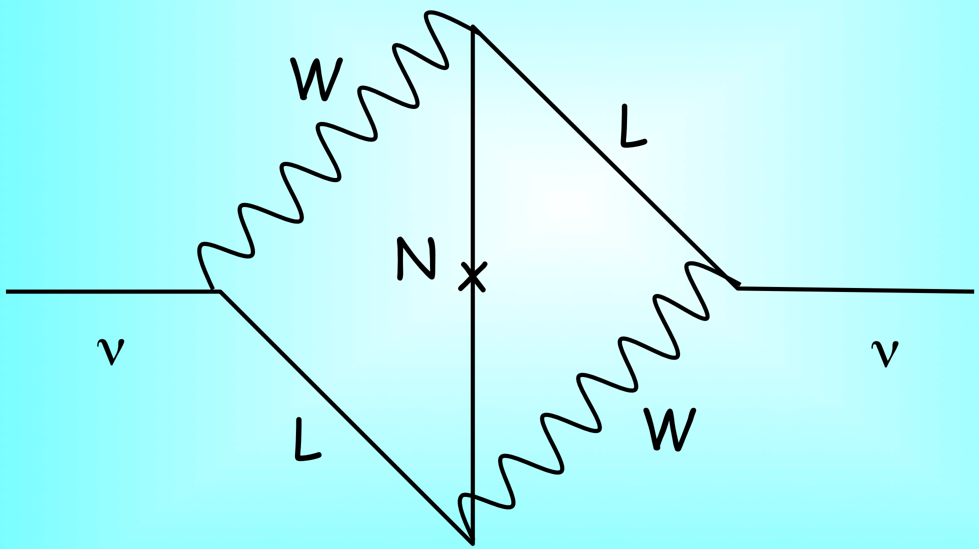
f and h are matrices of the couplings in the flavor basis

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

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

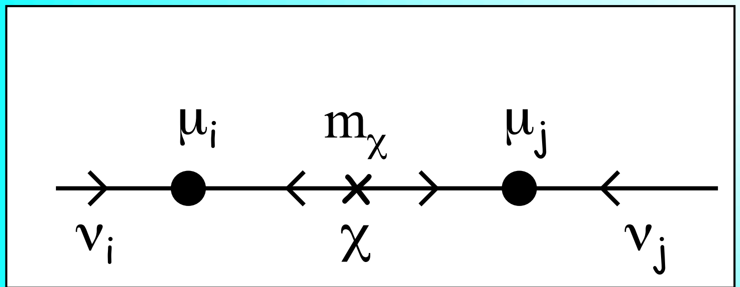
Neutrinos are not unique:
→ can mix with neutralinos if R-parity is broken
→ new mechanism of neutrino mass generation

R-parity violating SUSY

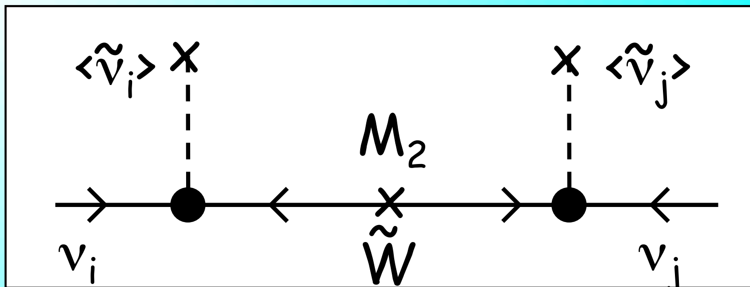
Superpotential: Z_3 - baryon triality (Ibanez, Ross)

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

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



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

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

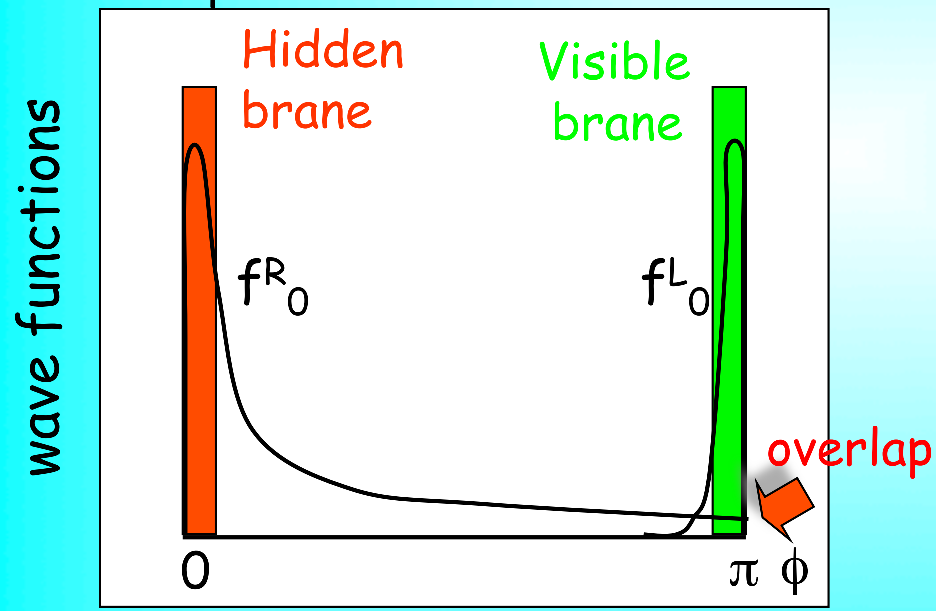
As in strings

Overlap in extra dimensions

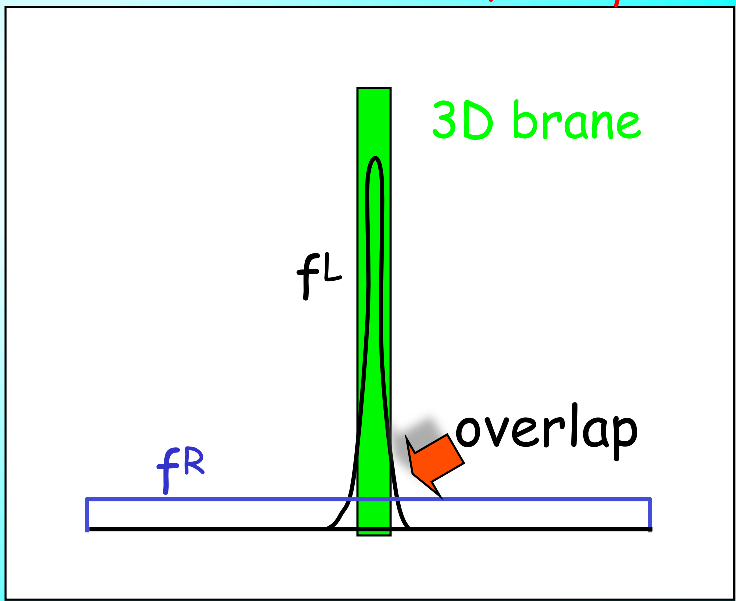
Right handed components are localized differently in extra dimensions

small Dirac masses due to overlap suppression:

Warped extra D *Grossman Neubert*



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



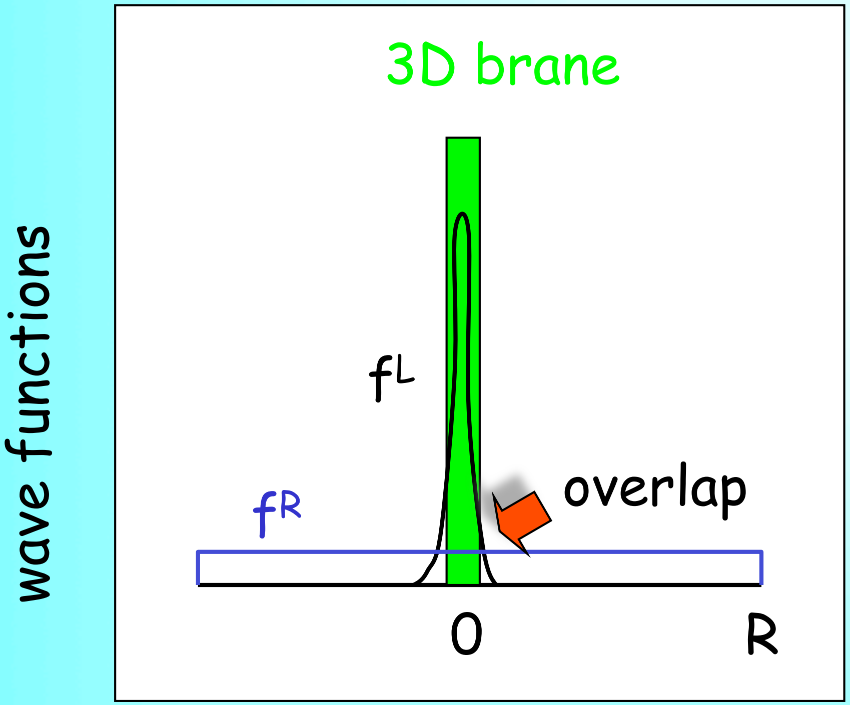
$$m\, \varepsilon\, \overline{f^L}\, f^R \; + \; h.\, c.$$

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: $1/\sqrt{M^\delta\, V_\delta}$

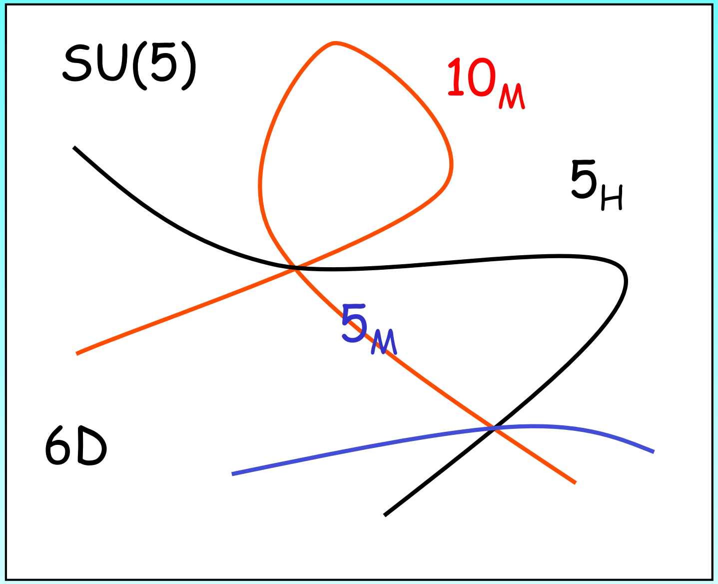
$$m_D = \lambda\, v_{EW} \left(\frac{1}{M^\delta\, V_\delta} \right)^{\frac{1}{2}} = \lambda\, v_{EW}\, M/M_{Pl}$$

String engineering

Playing with geometry of internal space

Generic elements of the F-theory:

V .Bouchard, J J Heckman
J Seo, C. Vafa



1. In the lowest order:
Yukawa couplings are given by overlap of the 6D fields localized on ``matter curves" .

They appear at intersection of three matter curves which correspond to matter and Higgs fields.

This leads to singular Yukawa matrices:

$$Y_{ij} \sim z_i \; z_j$$

Only one eigenvalue (mass) is non-zero

... continued

2. Masses of lighter quarks and leptons appear as result of corrections due to interactions with the background gauge fields.

Corrections are determined by the gauge coupling:

$$\varepsilon \sim \sqrt{\alpha_{GUT}} \qquad \sim (M_* R_i)^{-2}$$

where $R_i \sim M_{GUT}^{-1}$ $\quad M_*^4 = \alpha_{GUT}^{-1} M_{GUT}^4$

Mass matrices appear then as powers of these parameters

...continued

3. GUT symmetry is broken in the hypercharge direction → Expansion parameters and powers for different fermions are different

Origin of Yukawa structures is in the gauge sector!

4. Large lepton mixing is related to weak mass hierarchy of neutrinos and originates from properties of RH neutrinos or objects which play role of the RH neutrinos

- Kaluza-Klein seesaw
  from integration of the KK modes: $M = \frac{1}{\Lambda_{UV}} L H_u \; L H_{\underline{u}}$

$$U_{PMNS} = \begin{pmatrix} 1 & \varepsilon^{1/2} & \varepsilon \\ \varepsilon^{1/2} & 1 & \varepsilon^{1/2} \\ \varepsilon & \varepsilon^{1/2} & 1 \end{pmatrix}$$

up to coefficients of the order 1

$\sin\theta_C \sim \sqrt{\alpha_{GUT}}$

Froggatt-Nielsen is back?

Additional slides

Neutrino symmetry?

Maximal 2-3 mixing

Can both features be accidental?

Zero 1-3 mixing

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

Neutrino mass matrix in the flavor basis:
For charged leptons: D = 0

$$\begin{pmatrix} A & B & B \\ B & C & D \\ B & D & C \end{pmatrix}$$

Often related to equality of neutrino masses

Discrete symmetries S_3, D_4

Are quarks and leptons fundamentally different?

Seesaw

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

  $M_R = f_S \langle S \rangle = f_S v_R$

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

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

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

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

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

Flavor structure of two contributions correlates

Problem:

- Strong hierarchy of the quark and charged lepton masses

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

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

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

Possible solutions:

Type II seesaw: no dependence on m_D

Special structure of M_R which compensate strong hierarchy in m_D

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

Seesaw enhancement of mixing

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

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

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

Special structure of M_R → Large lepton mixing

Two possibilities:

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

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

Strong interfamily connection (pseudo Dirac structures)

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

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?

U_e3 - expectations

- Naively $\boxed{\sin\theta_{13} \sim \sin\theta_{12} \times \sin\theta_{23}}$ $\sim$ 0.3 - 0.5

  excluded which implies dominant structures or/and degeneracy in the mass matrix

- A bit seriously

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

Mass scales: $\sqrt{\Delta m_{sun}^2}$ $\sqrt{\Delta m_{atm}^2}$

$\Rightarrow$ $\boxed{\sin\theta_{13} \sim \sqrt{\Delta m_{sun}^2 / \Delta m_{atm}^2}}$ $\sim$ 0.15 - 0.20

With comparable contribution from the charge leptons

If there is no cancellation: $\boxed{\sin^2\theta_{13} \sim 0.01 - 0.05}$

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

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

Akhmedov et al

- Radiative generation of $\sin\theta_{13}$ ➡ $\sin\theta_{13} \sim 0.01 - 0.1$
- From charged leptons: $\sin\theta_{13} \sim \sqrt{\frac{2\, m_e}{3\, m_\mu}} \sim 0.02$
- Type II seesaw, minimal SO(10) GUT $\quad \sin\theta_{13} \sim O(1) \sin\theta_c$

Generic problem

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

Mechanism of mass generation

Yukawa couplings

VEV's

VEV alignment

- different contributions
- high order corrections

follow from independent sectors

Yukawa sector   Scalar potential

TBM

All these components should be correlated

``Natural" – consequence of symmetry?

tune by additional symmetries

one step constructions do not work

Screening of Dirac structure

M. Lindner
M. Schmidt
A.S.

$$m = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_D^T \\ 0 & M_D & M_S \end{pmatrix} \quad \begin{matrix} \nu \\ N \\ S \end{matrix}$$

Additional fermions

$m_D \ll M_D \ll M_S$

Double (cascade) seesaw

R. Mohapatra
J. Valle

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

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

M_S – Majorana mass matrix of new fermions S

If $M_D = A^{-1} m_D$ → $m_\nu = A^2 M_S$

$A \sim v_{EW}/M_{GU}$

A.S.

m_D similar (equal) to quark mass matrix - cancels

Structure of the neutrino mass matrix is determined by M_S
-> physics at highest (Planck?) scale immediately

Increasing m_D

$$m_D = \frac{\alpha\, \eta\, m_{3/2}\, v_{EW}}{M_{Pl}}$$

η -renormalization effect

$M_{Pl} \to M_{GUT}$

$m_{3/2} \dashrightarrow 10^2$ TeV

``Consistent anomaly mediation''
H. Murayama

Large α

S. Abel, A. Dedes
K. Tamvakis

$$K = 1/M\ P(S, \sigma, \sigma^*)\, L\, H\, N + h.c.$$

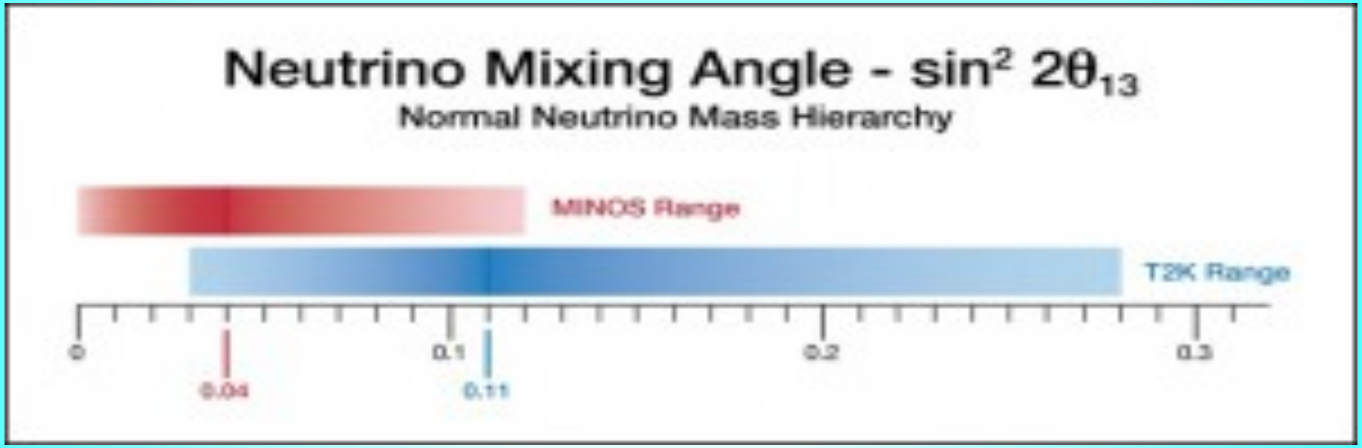
$M = 10^{17}$ GeV - cut off
σ – fields of the Hidden sector

Dominant contribution to the mass:
$\sim v_{EW}\ F_\sigma/M^2$

$F_\sigma = \sqrt{3} M_{Pl}\, m_{3/2}$

$$m_D = \frac{\eta\, m_{3/2}\, v_{EW}}{M} \frac{\sqrt{3} M_{Pl}}{M} \sim 0.05 \text{ eV}$$

Implications



Strongly broken TBM?

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

Quark-lepton complementarity:

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

No special symmetry in the leptonic sector

Hints from data

Scale of neutrino mass

See-saw

Grand Unification

→ quark-lepton correspondence

Extra dimensions

→ for Dirac masses

Symmetry

accidental: absence of RH neutrinos

Pattern of lepton mixing

Flavor symmetries

``Anarchy''

→ Mass hierarchy

→ Koide mass relation for charged leptons

Comments:

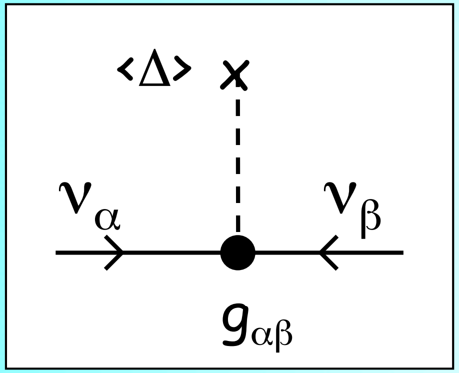
Data show both order, regularities and
some degree of randomness

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?

Higgs Triplet mechanism



E. Ma

No RH neutrinos

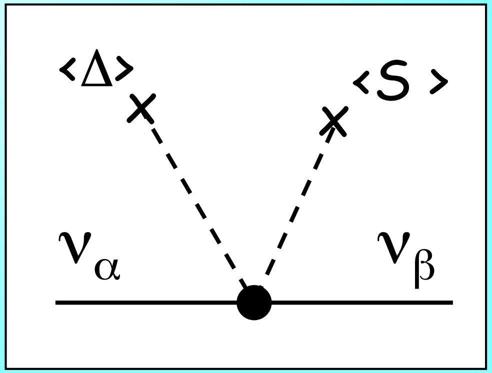
Higgs triplet: (Δ^{++}, Δ^{+}, Δ^{0})

EW precision measurements:
$\langle \Delta^0 \rangle / \langle H \rangle < 0.03$

No triplet Majoron -> coupling $\mu \, \Delta \, H \, H$

If $g_{\alpha\beta} \sim 1$, $\langle \Delta^0 \rangle \sim 1$ eV

Effective coupling



If M_Δ, $\mu \gg \langle H \rangle$:
$\langle \Delta^0 \rangle \sim \langle H \rangle^2 \mu / M^2$

Seesaw type II

If $M_\Delta \sim \langle H \rangle$, $\mu \ll \langle H \rangle$
$\langle \Delta^0 \rangle \sim \mu$

pseudo Majoron
mass $\sim \mu \sim 0.03 \langle H \rangle$
excluded by
Z^0 -width

SUSY violation & neutrino mass

Observation:

$$m = \frac{m_{3/2}\, v_{EW}}{M_{Pl}} \sim 10^{-4}\, eV$$

$m_{3/2}$ - gravitino mass

Mass term which mixes active neutrinos with singlets e.g.

- neutrino-modulino mixing or
- Dirac mass mass terms

K. Benakli, A.S.

Corresponds to Yukawa interaction λLSH with $\lambda = m_{3/2} / M_{Pl}$

It can be generated either by non-renormalizable terms in the superpotential or from the Kahler potential similarly to appearance of the μ-term in Giudice-Masiero mechanism

$$K = 1/M_{Pl}\ P(S, z, z^*)\, LH + h.c.$$

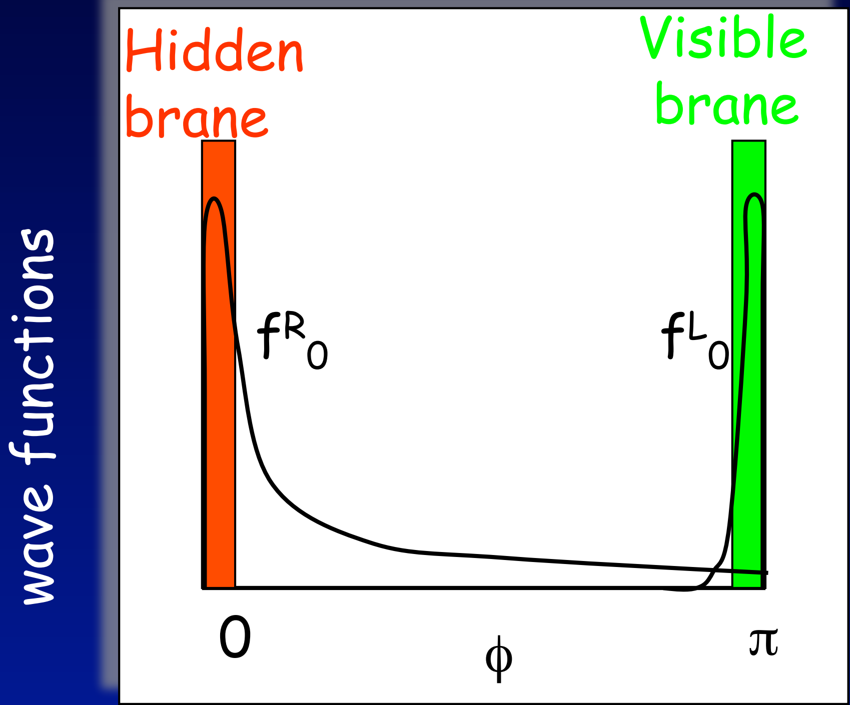
z - Wilson lines...

Too small mass?

...in warped extra D

Grossman
Neubert
Huber, Shafi...

In Randall -Sundrum (non-factorizable metric)
Setting: 1 extra D S^1/Z_2



RH neutrinos - bulk zero mode localized on the hidden brane

On visible brane:

$$f^R_0(\pi) \sim \varepsilon^{\nu - 0.5}$$

$\nu = m/k$
$m \sim M$
Dirac mass in 5D

$$\varepsilon = e^{-kr_c\pi} = \frac{v_{EW}}{M} = 10^{-16}$$

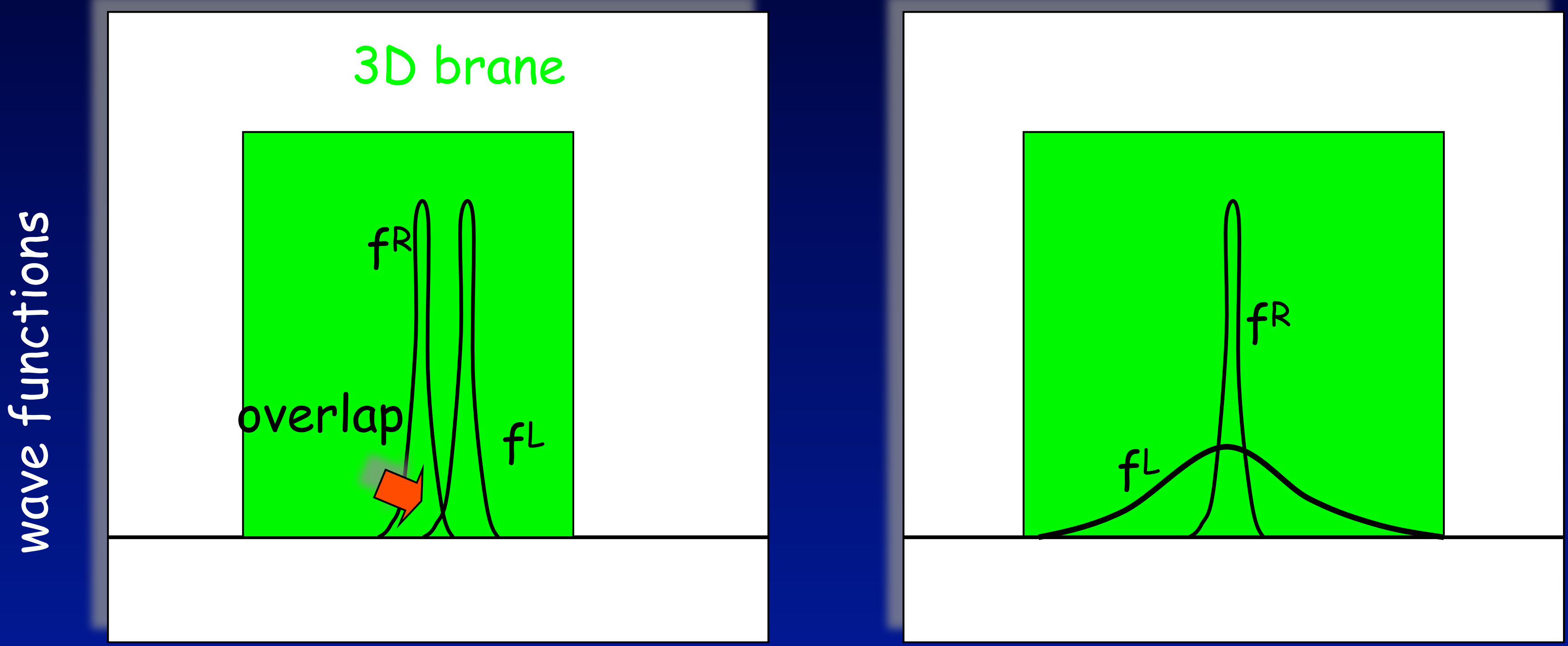
M - fundamental Planck scale
r_c radius of extra D
$k \sim M$ - curvature parameter

$$m_D = Y f^R_0(\pi)\, v_{EW} \sim M \left(\frac{v_{EW}}{M}\right)^{\nu + 1/2}$$

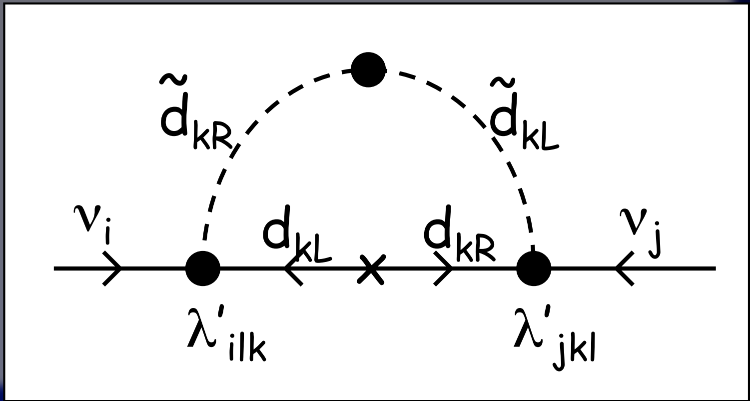
$\nu \sim 1.1 - 1.6$

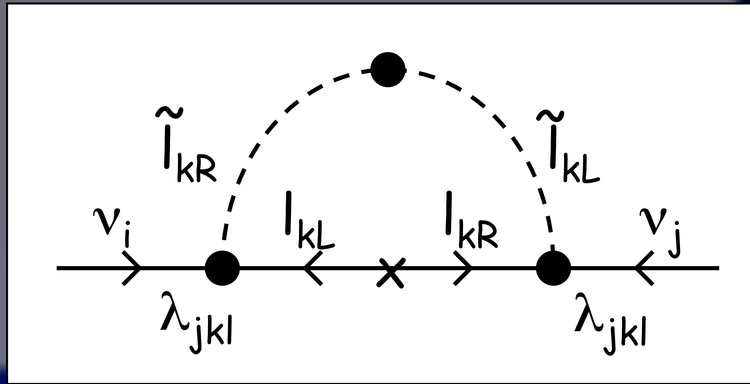
... on the fat brane

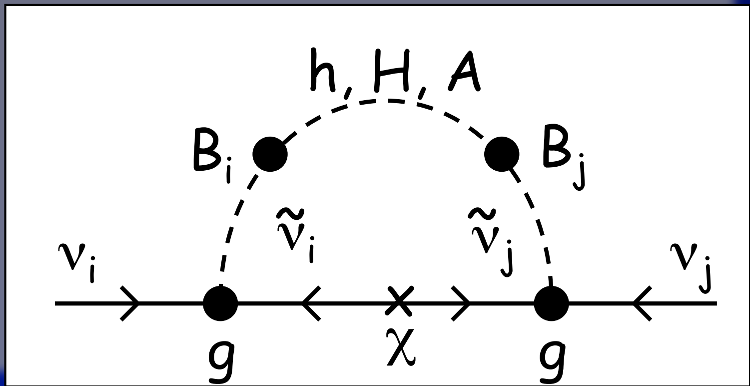
Arkani-Hamed, Schmaltz

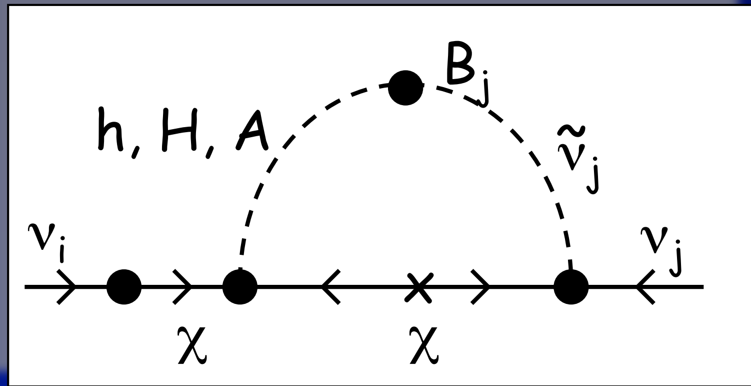


RpV: loops









B_m- soft symmetry breaking parameter

…

New physics

L-R symmetric models

Neutrino Mass

Grand Unification

Supersymmetry

Flavor symmetry

Extensions of Electroweak theory

Superstrings

Extra Dimensions

Physics related to violation of fundamental symmetries

μ - term mixing

Model: SU(5) GUT R-symmetry

R.Kitano

Matter: $\bar{F}(\bar{5}, 1)$, $T(10,1)$, $N(1, -1)$ ⇐ R-charge is different

Higgs : $H(5, 0)$, $\bar{H}(5, 0)$
$H'(5, 2)$, $\bar{H}'(5, 0)$ ⇐ New higgs

Superpotential: $\boxed{W = f\,\bar{F}\,H'\,N + M_H H'\,\bar{H}' + \text{usual terms}}$...

couples with new higgs

SUSY breaking ->
R-symmetry breaking: $\boxed{W_R = \mu\,H\,\bar{H} + \mu'\,H\,\bar{H}'}$ new μ-term

Mixing of
H and H'

$H \quad \mu'\,\bar{H}' \quad M_H \quad H'$

⇒ $\boxed{f\,\mu'/M_H\,\bar{F}\,H\,N}$

⇒ $\boxed{m_\nu = f\,\mu'\langle H\rangle/M_H}$

Top - down

String theory

GUT

Existence of a number O(100) of singlets of SM and GUT symmetry group

Several U(1) gauge factors

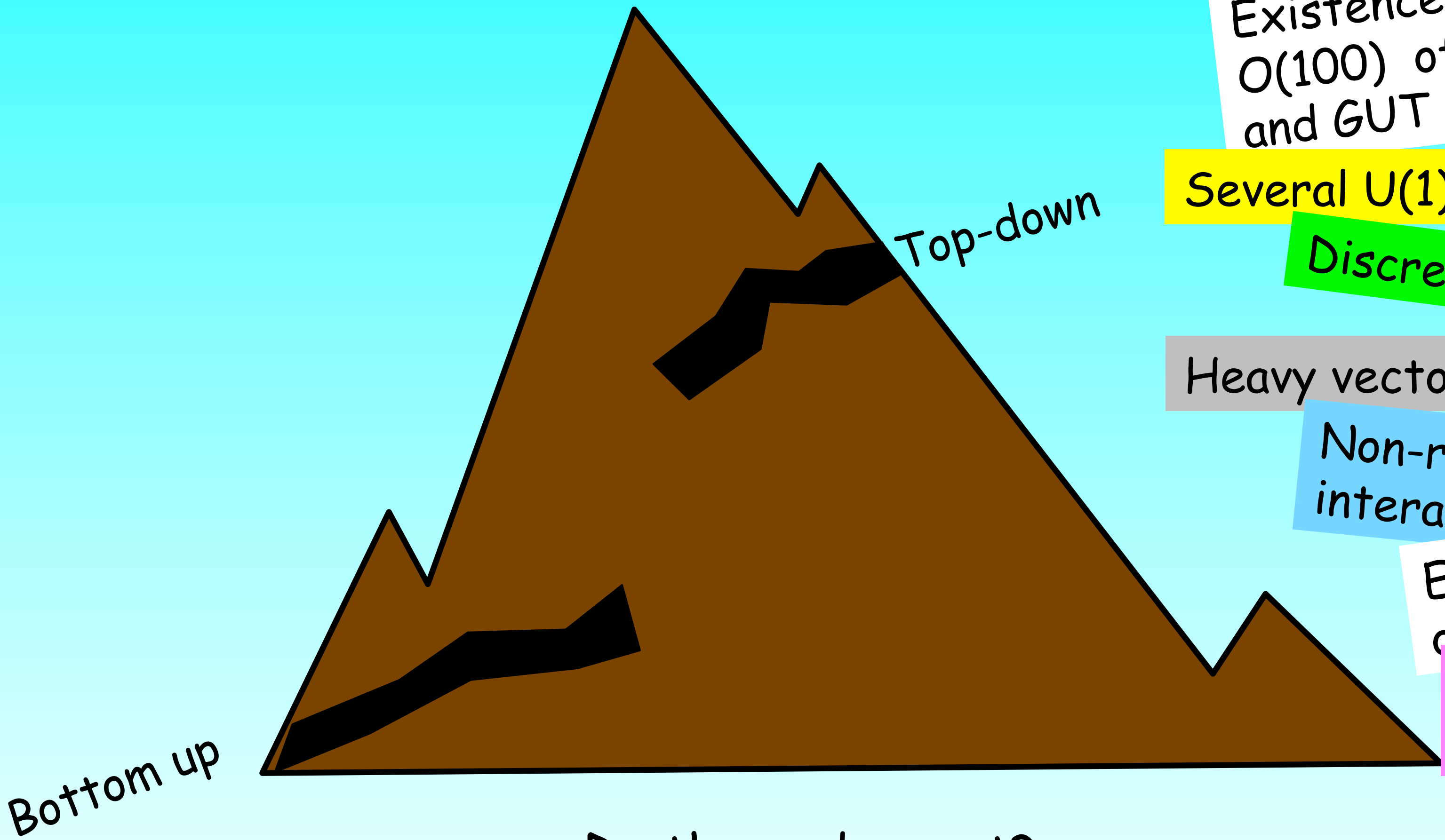
Discrete symmetries

Heavy vector-like families

Non-renormalizable interaction

Explicit violation of symmetry

Incomplete GUT multiplets



Do the ends meet?

1-3 mixing: global fit