Discrete Dark Matter and the reactor mixing angle

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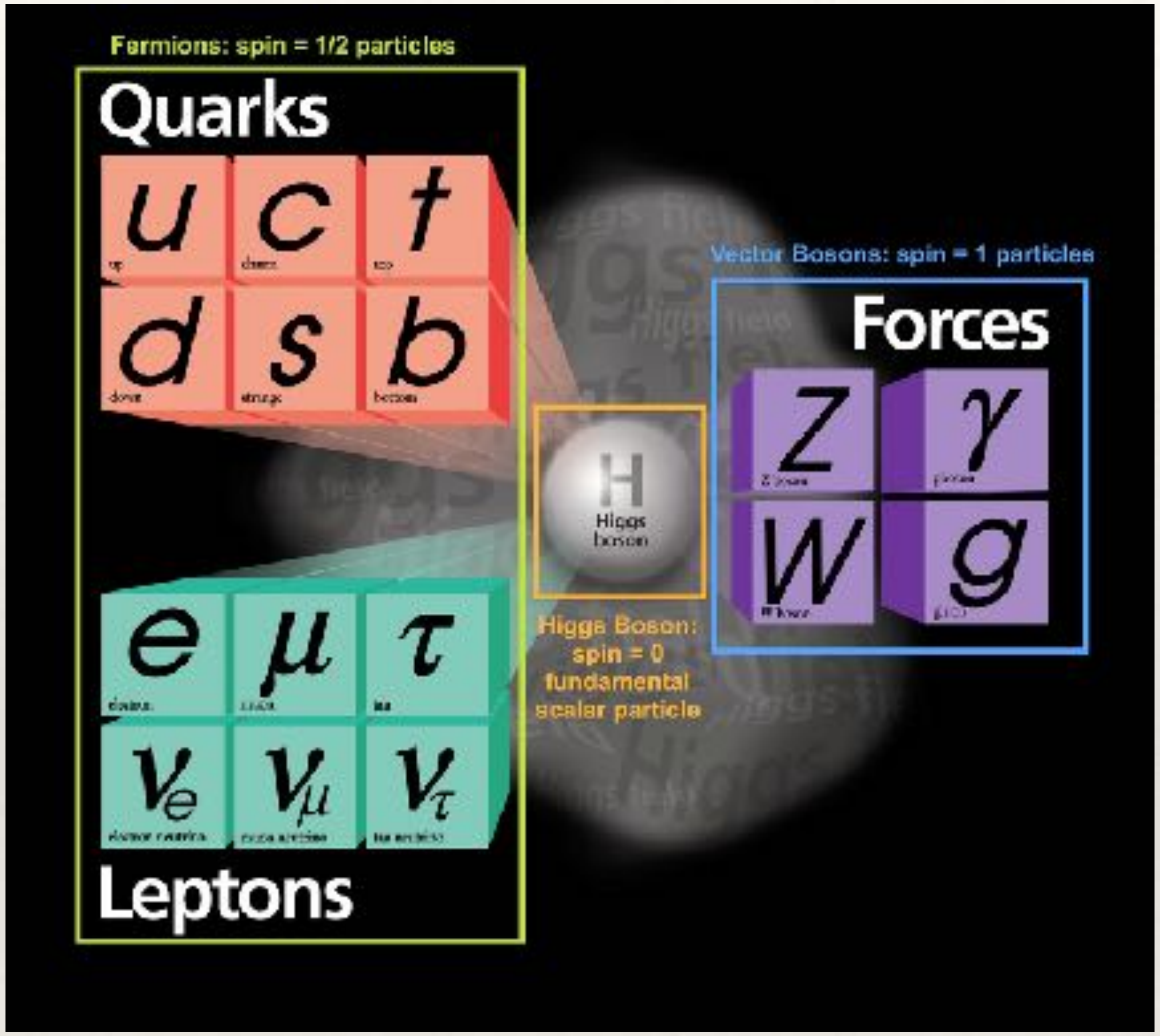
Flasy 2018, University of Basel

Plan of the talk 🏆

- Neutrino oscillation and masses
- Dark Matter Stability

  DDM and texture zeros
- Summary and conclusions

The Standard Model



EWSB mechanism

3 generations

neutrino oscillations (massive neutrinos)

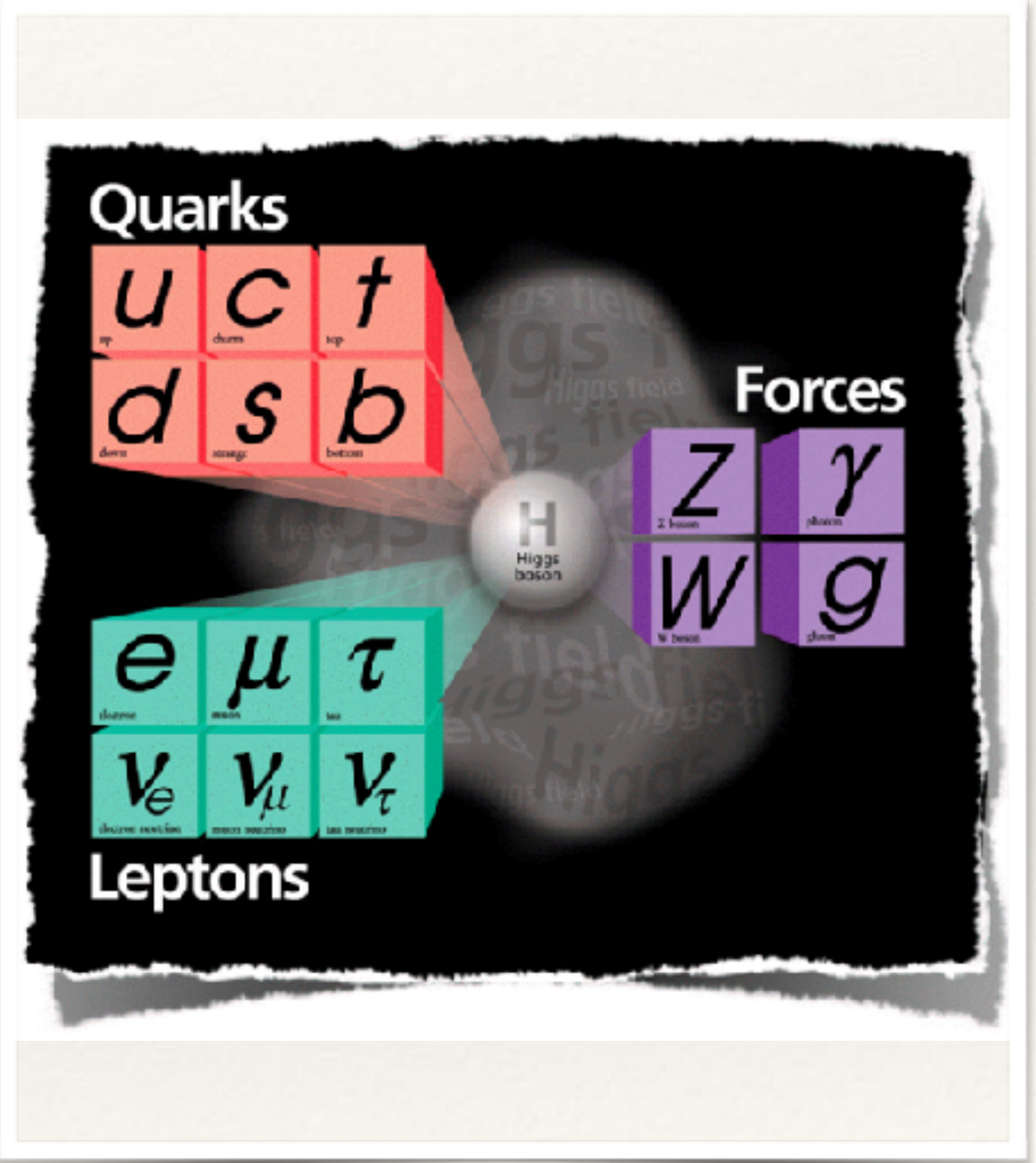
The Standard Model

BSM

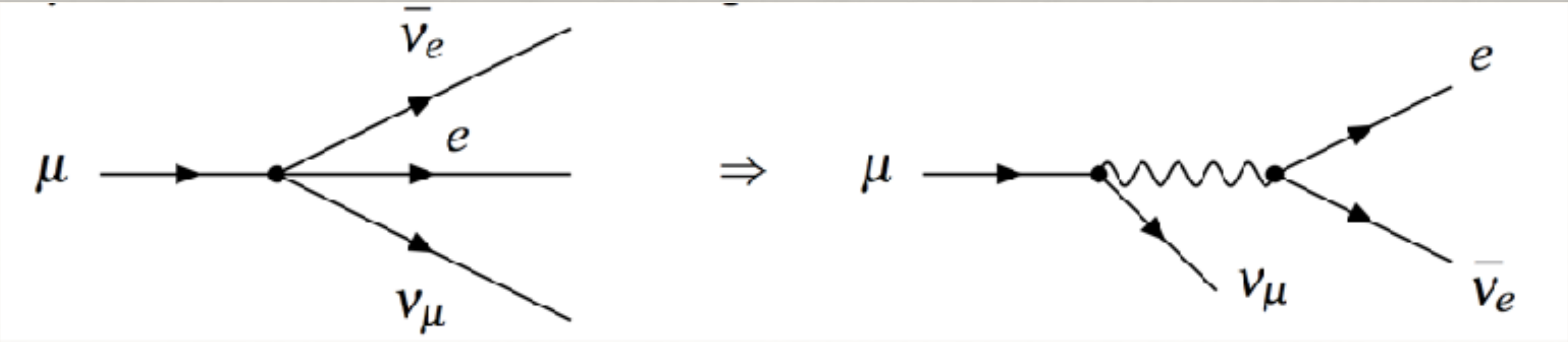
- Dark Matter
- Neutrino masses
- BAU
- Dark Energy

*Theoretical issues

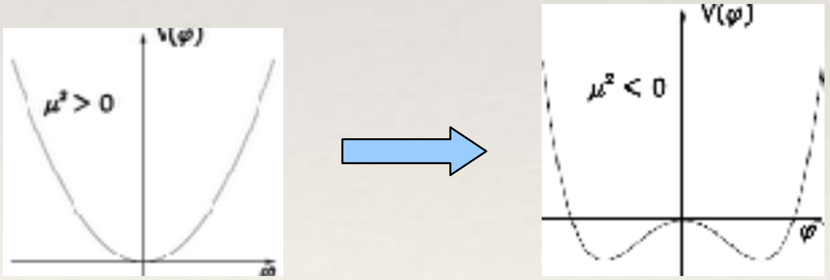
- Number of families
- Masses and mixings
- Hierarchy problem



Higgs mechanism



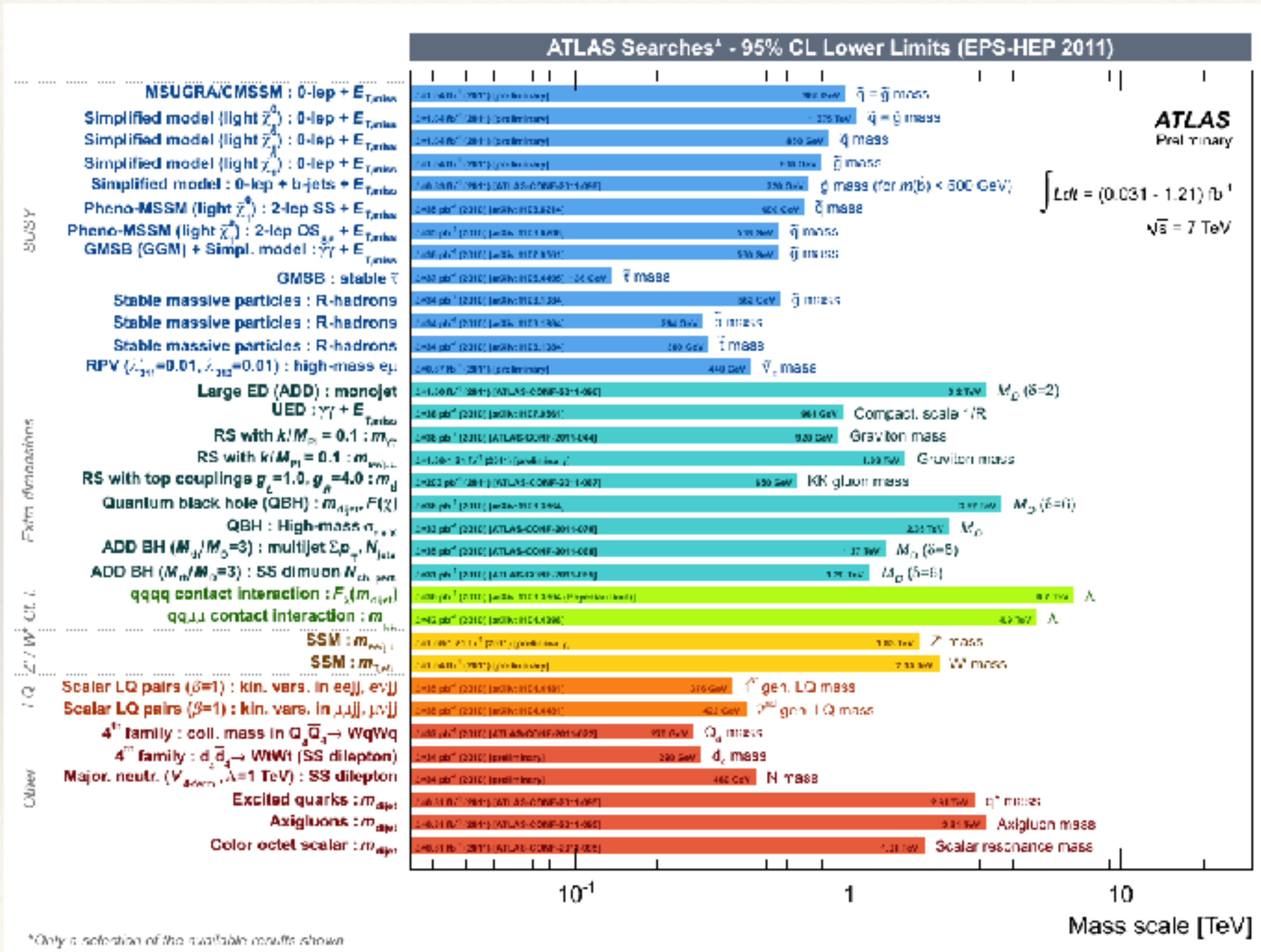
W's and Z boson masses



Brout-Englert-Higgs Mechanism

BSM?

Limits on some scenarios by LCH



Yukawas and masses

$$
\begin{aligned}
\mathcal{L} = & \, i\overline{L'_{\alpha L}}\not{D}L'_{\alpha L} + i\,\overline{Q'_{\alpha L}}\not{D}Q'_{\alpha L} + i\overline{l'_{\alpha R}}\not{D}l'_{\alpha R} \\
& + i\overline{q'^{D}_{\alpha R}}\not{D}q'^{D}_{\alpha R} + i\overline{q'^{U}_{\alpha R}}\not{D}q'^{U}_{\alpha R} - \frac{1}{4}\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
& + \left(D_{\rho}\Phi\right)^{\dagger}\left(D^{\rho}\Phi\right) + \mu^2\Phi^{\dagger}\Phi - \lambda\left(\Phi^{\dagger}\Phi\right)^2 \\
& - \left(Y'^{l}_{\alpha\beta}\,\overline{L'_{\alpha L}}\,\Phi\,l'_{\beta R} + Y'^{l*}_{\alpha\beta}\,\overline{l'_{\beta R}}\,\Phi^{\dagger}\,L'_{\alpha L}\right) \\
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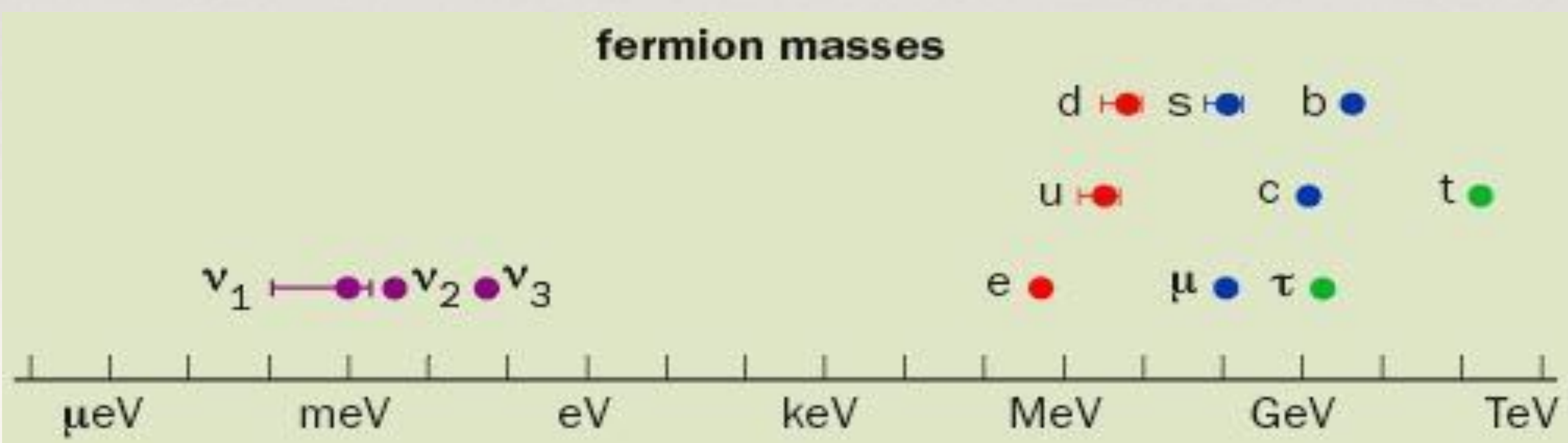
\end{aligned}
$$

} Yukawa Lagrangiana

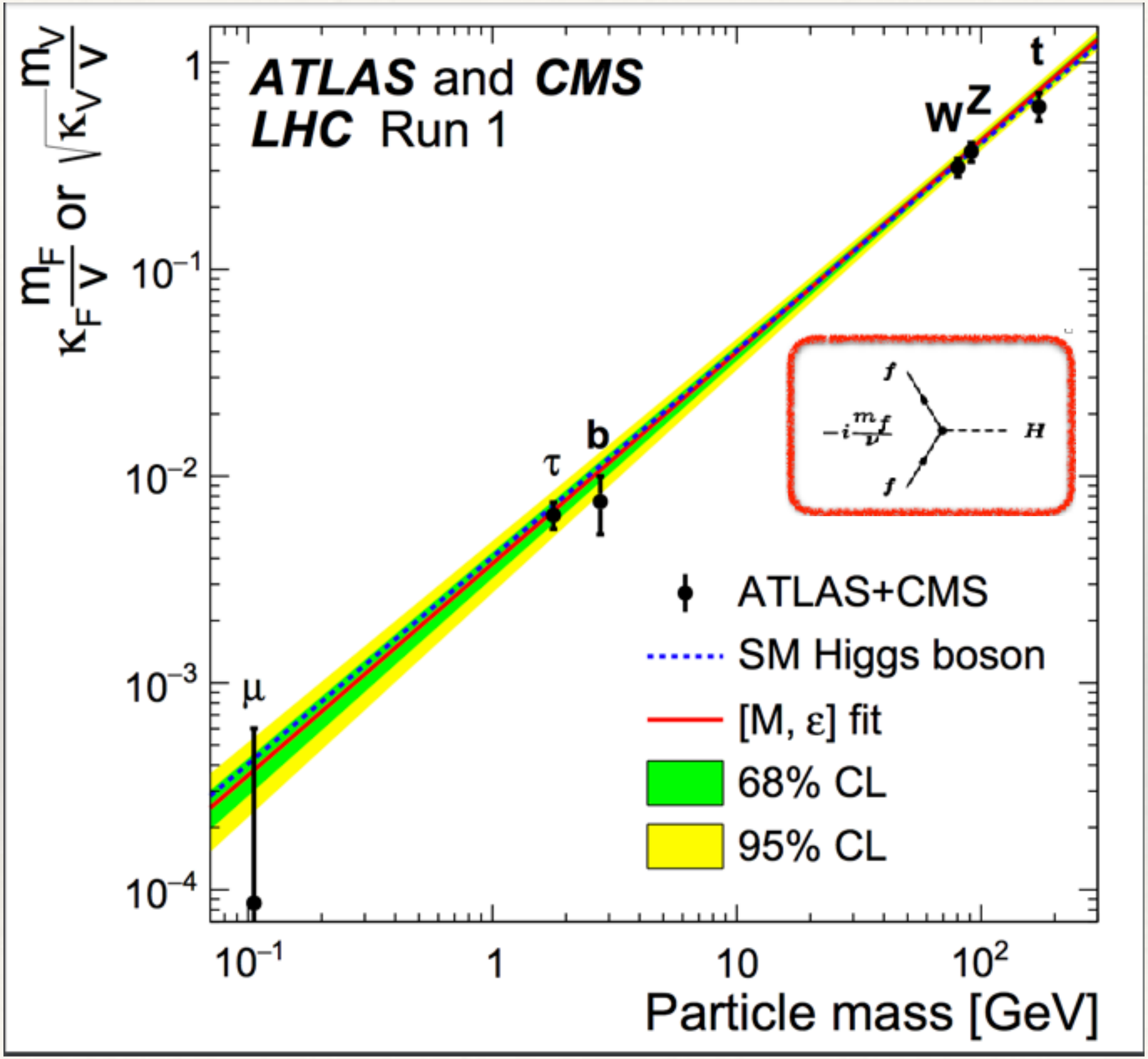
$$m_\nu << m_e << m_t$$

Very different Yukawa Couplings



$$Y_{\nu_e} : Y_e : Y_t$$

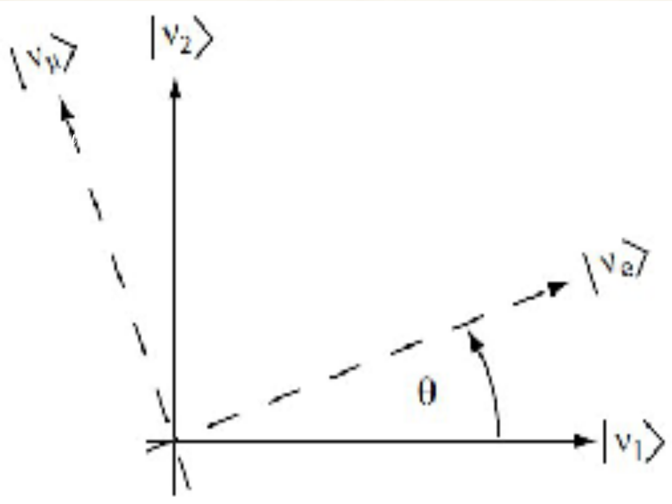
$$< 10^{-11} : 10^{-}6 : 1$$



ATLAS and CMS
LHC Run 1
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
Particle mass [GeV]
μ
τ
b
W
Z
t
$-i\frac{m_f}{v}$
f
f
H
ATLAS+CMS
SM Higgs boson
[M, ε] fit
68% CL
95% CL

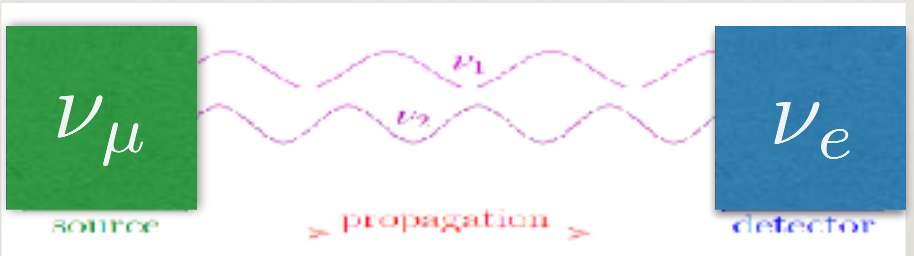
Neutrino masses

Neutrino oscillation



week eigenstates massive eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$P(\nu_\mu \to \nu_e) = |\langle \nu_e | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E_\nu}\right)$$

3 mixing angles and 2 squared mass differences

Neutrino mixings

parameter	best fit $\pm$ 1σ	2σ range	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.50 ± 0.03	2.44–2.57	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.34–2.47	2.31–2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/^\circ$	$34.5^{+1.2}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.67–5.83	4.45–5.99
$\theta_{23}/^\circ$	$47.7^{+1.2}_{-1.7}$	43.1–49.8	41.8–50.7
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.91–5.84	4.53–5.98
$\theta_{23}/^\circ$	$47.9^{+1.0}_{-1.7}$	44.5–48.9	42.3–50.7
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	2.03–2.34	1.96–2.41
$\theta_{13}/^\circ$	$8.45^{+0.16}_{-0.14}$	8.2–8.8	8.0–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	2.07–2.36	1.99–2.44
$\theta_{13}/^\circ$	$8.53^{+0.14}_{-0.15}$	8.3–8.8	8.1–9.0
δ/π (NO)	$1.21^{+0.21}_{-0.15}$	1.01–1.75	0.87–1.94
$\delta/^\circ$	218^{+38}_{-27}	182–315	157–349
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94
$\delta/^\circ$	281^{+23}_{-27}	229–328	202–349

de Salas, Forero, Ternes, Tortola, Valle (2018)

- 2 nearly maximal mixings
- One small $\mathcal{O}(\lambda_C)$
- CP violation

- 2 squared mass differences

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de Salas, Forero, Ternes, Tortola, Valle (2018)

PDG (2018)

$$V_{\rm CKM} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \rightarrow 0.844 & 0.516 \rightarrow 0.582 & 0.141 \rightarrow 0.156 \\ 0.242 \rightarrow 0.494 & 0.467 \rightarrow 0.678 & 0.639 \rightarrow 0.774 \\ 0.284 \rightarrow 0.521 & 0.490 \rightarrow 0.695 & 0.615 \rightarrow 0.754 \end{pmatrix}$$

Fermion masses

$$
\begin{aligned}
\mathcal{L} = {} & i\overline{L'_{\alpha L}}\not{D}L'_{\alpha L} + i\,\overline{Q'_{\alpha L}}\not{D}Q'_{\alpha L} + i\overline{l'_{\alpha R}}\not{D}l'_{\alpha R} \\
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} Yukawa Lagrangiana

Fermion masses:

m_e	$.5\ MeV$
m_d	$4.8\ MeV$
m_u	$2.3\ MeV$
m_μ	$105\ MeV$
m_s	$95\ MeV$
m_c	$1.275\ GeV$
m_τ	$1.776\ GeV$
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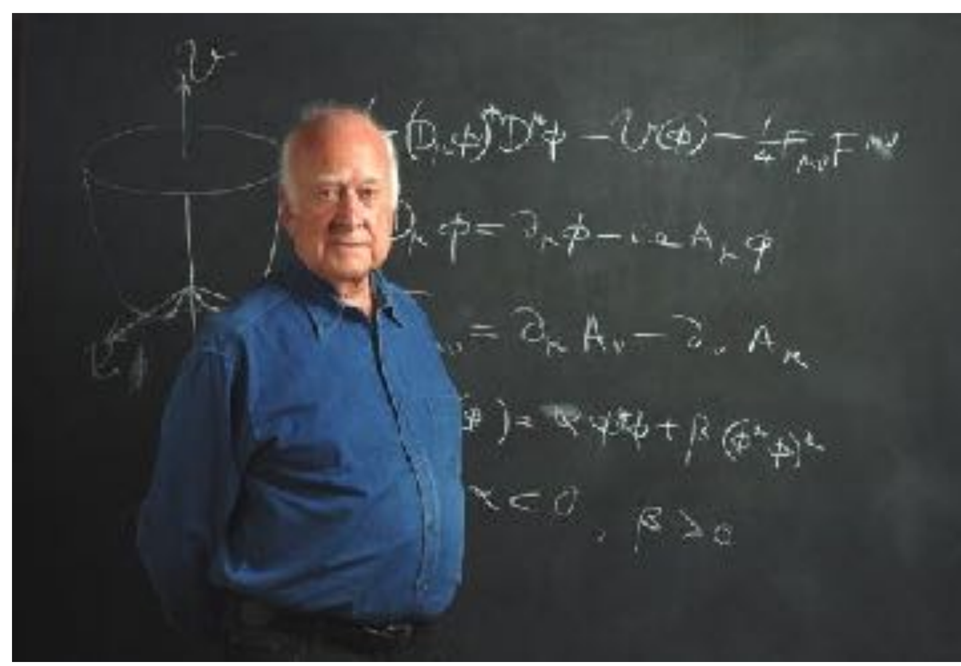

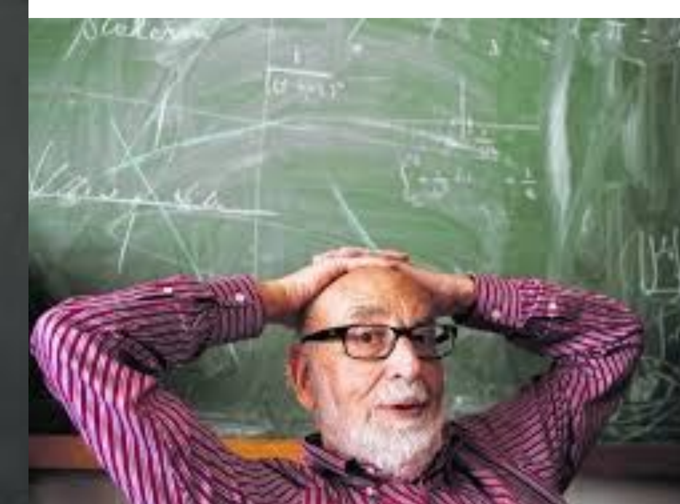

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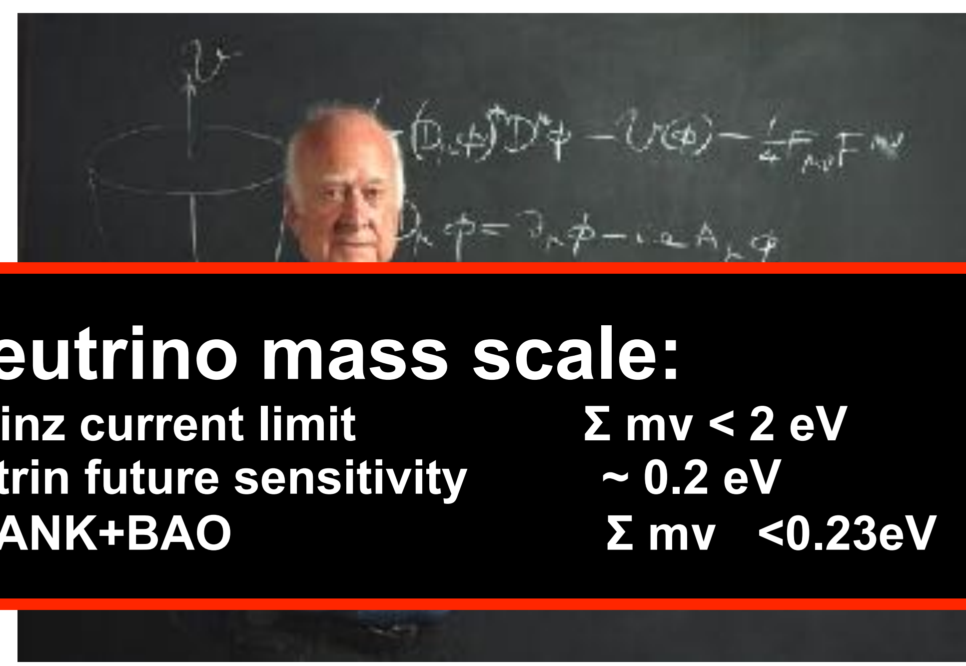
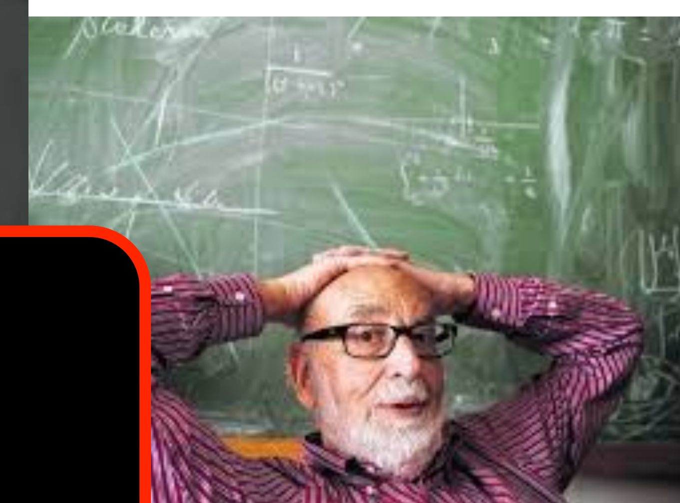




Neutrino mass scale:

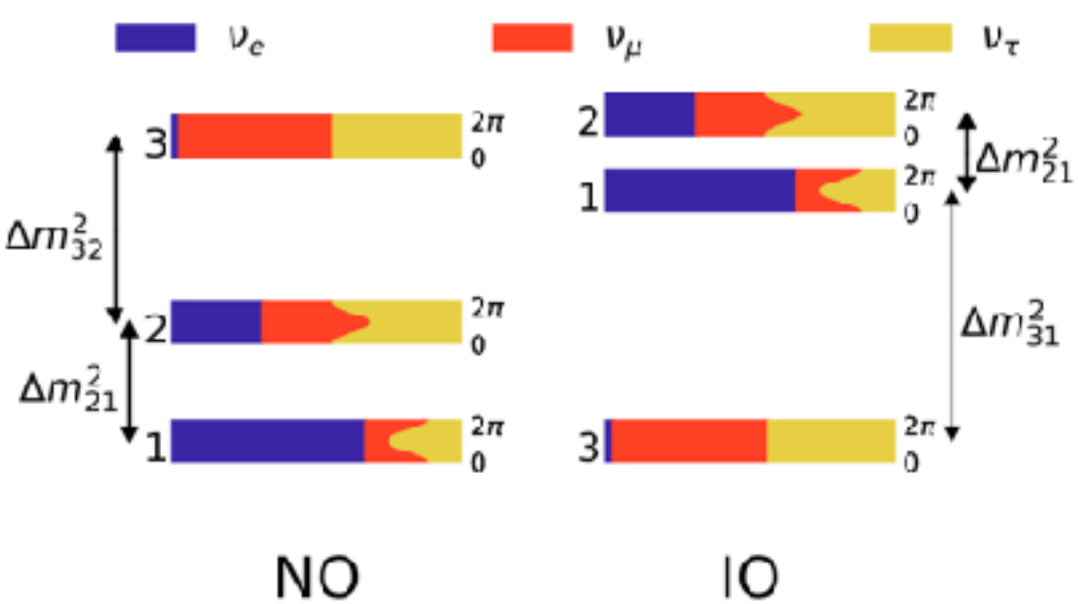
Mainz current limit	Σ mν < 2 eV
Katrin future sensitivity	~ 0.2 eV
PLANK+BAO	Σ mν <0.23eV

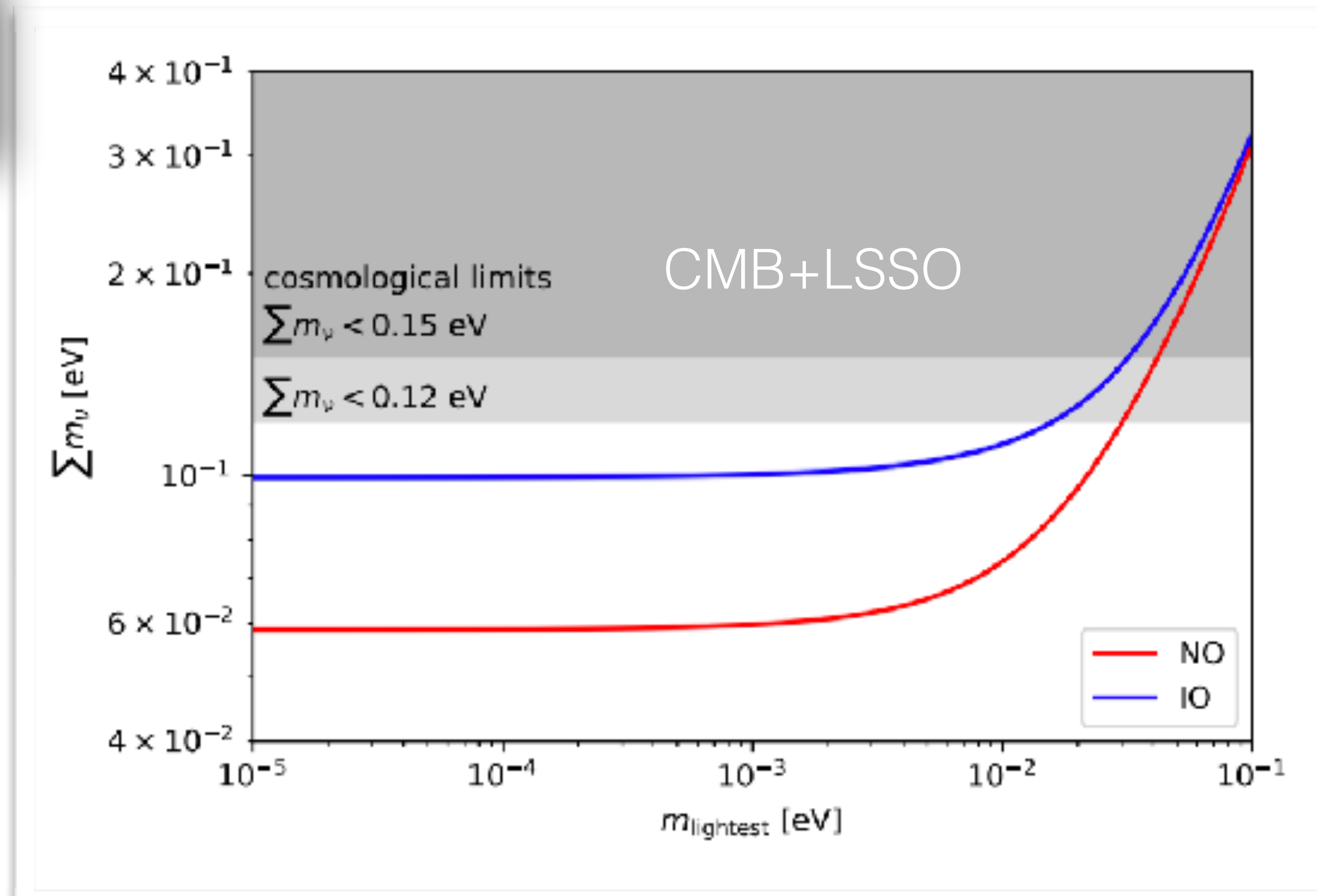
Neutrino masses Cosmology

de Salas, Gariazzo, Mena, Ternes, Tortola (2018)

$$\sum m_\nu^{\rm NO} = m_1 + \sqrt{m_1^2 + \Delta m_{21}^2} + \sqrt{m_1^2 + \Delta m_{31}^2}\,,$$

$$\sum m_\nu^{\rm IO} = m_3 + \sqrt{m_3^2 + |\Delta m_{31}^2|} + \sqrt{m_3^2 + |\Delta m_{31}^2| + \Delta m_{21}^2}$$

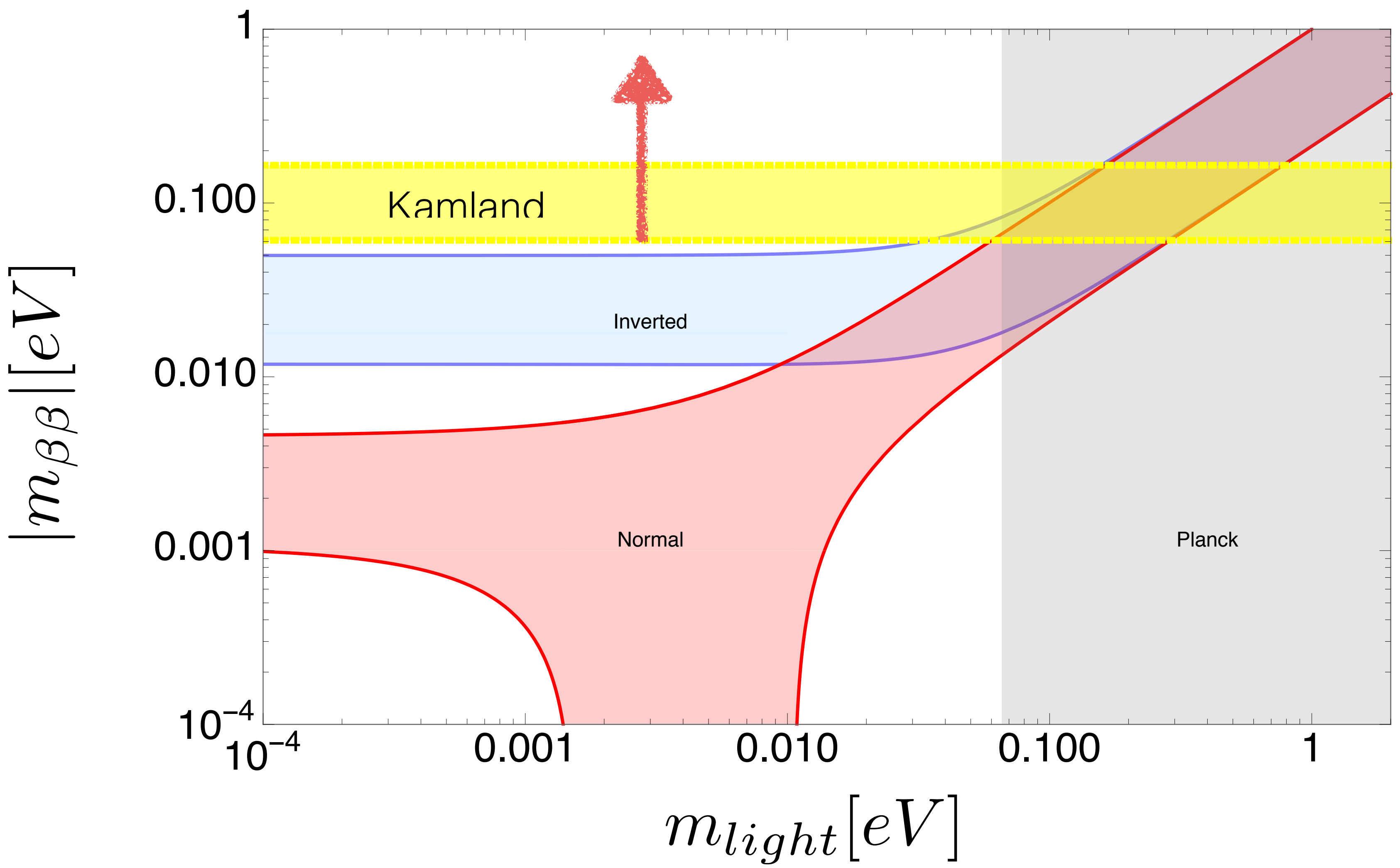




Neutrinoless double beta decay

$$m_{\beta\beta} = \sum_{k=1}^{N} e^{i\alpha_k} |U_{ek}|^2 m_k$$

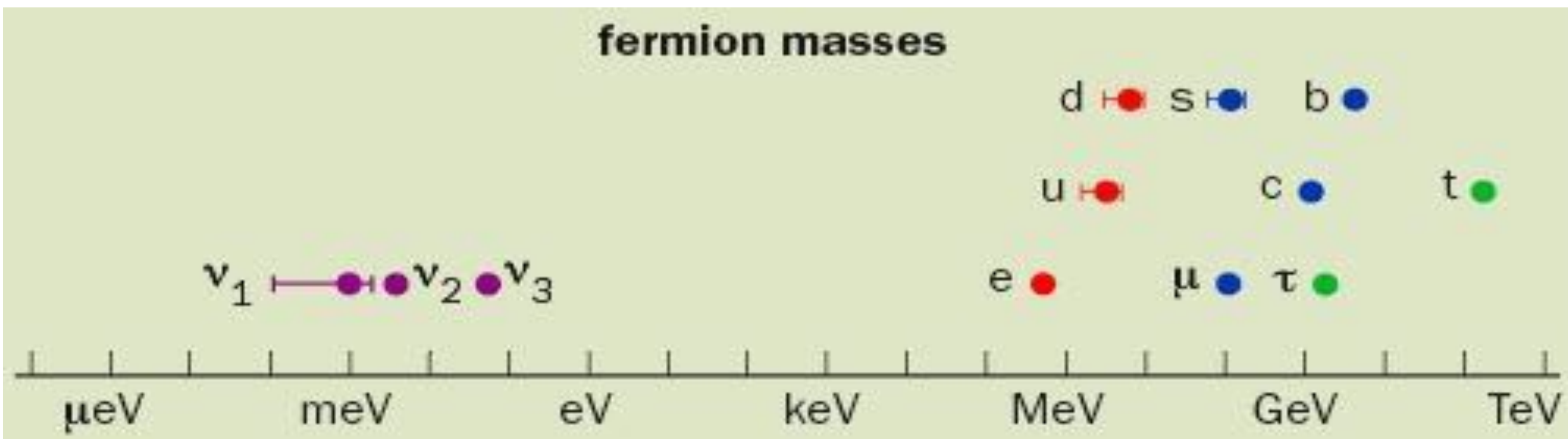
- **If neutrinos are Majorana particles**



11 neutrino mass matrix m_{ee}

Dirac neutrino masses

- **If we impose Lepton number then the neutrinos are Dirac particles just like quarks and charged leptons**



- **many orders of magnitude**

m_ν	$< 1\ eV$
m_e	$.5\ MeV$
m_t	$174\ GeV$

$$m_\nu << m_e << m_t$$

The Yukawa couplings are very different

$$Y_{\nu_e} : Y_e : Y_t$$

$$< 10^{-11} : 10^-6 : 1$$

Neutrino masses

How can we give mass to the neutrinos?

- Neutrinos are neutral particles
- If we add a Right-Handed neutrino (singlet of SM) then we have the Yukawa coupling with the Higgs (like quarks and leptons)

$$\lambda_{\alpha i} \bar{L_\alpha} \epsilon H^\star N_i$$

- But there is no symmetry that forbids also this term

$$M_i \bar{N}_i N_i$$

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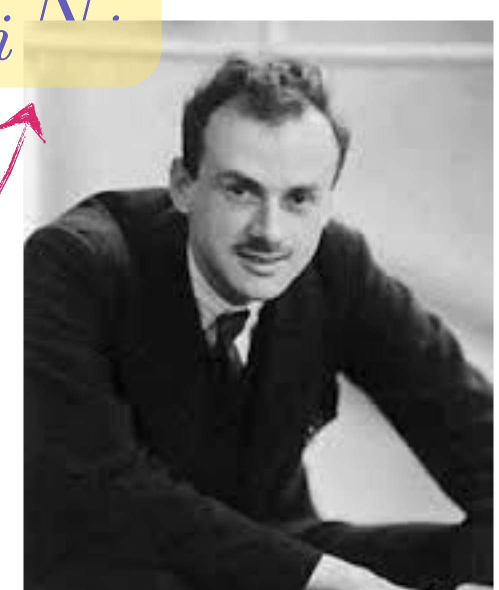
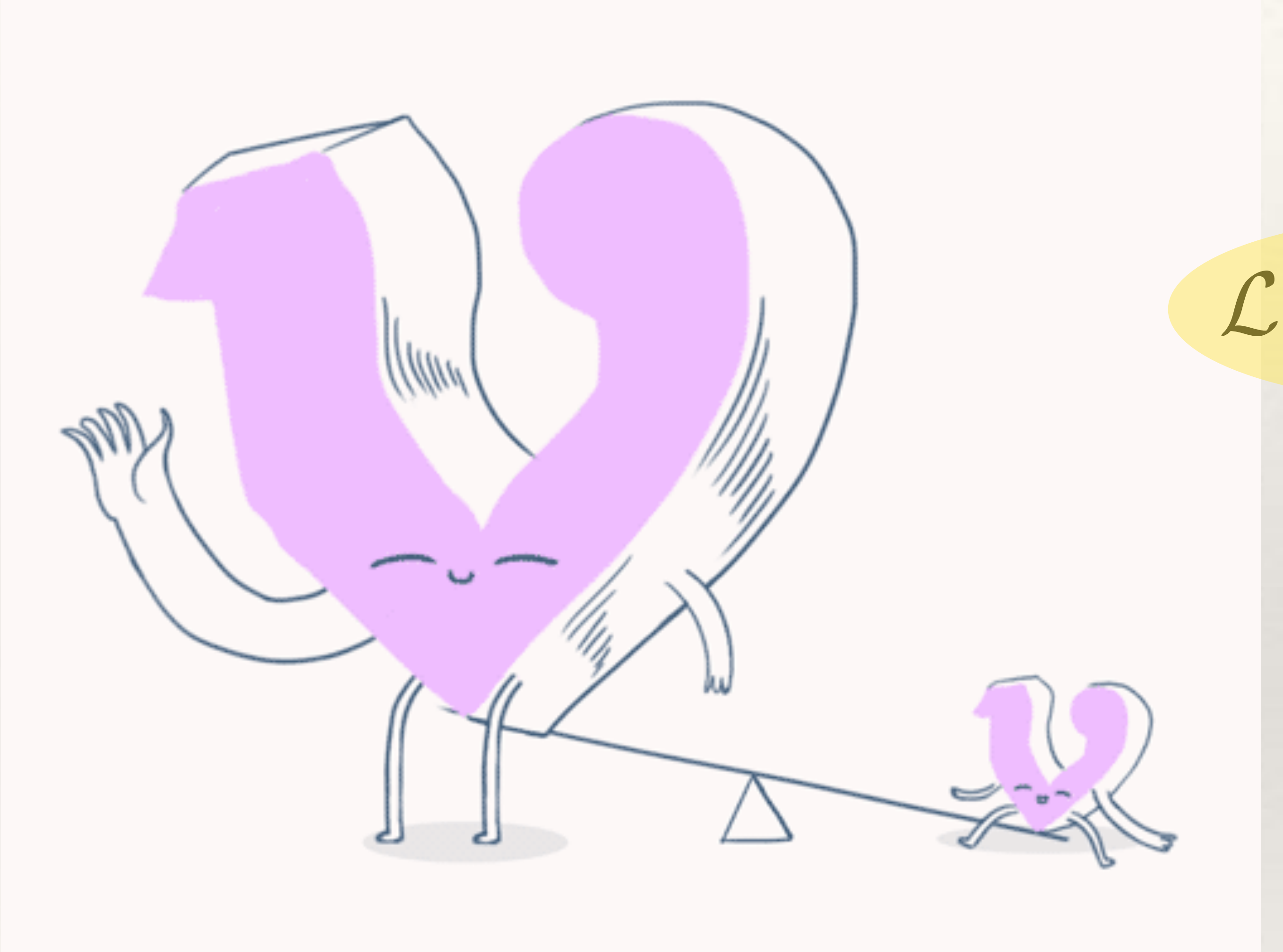


Vs.

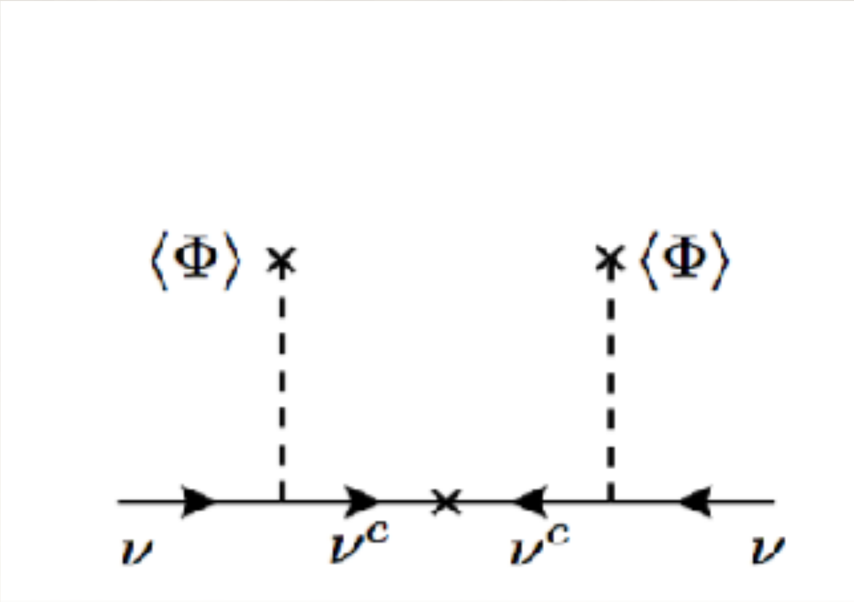
See-Saw



Symmetry magazine

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5$$

$$\mathcal{L}_5 = LL\Phi\Phi \qquad \Delta L = 2$$



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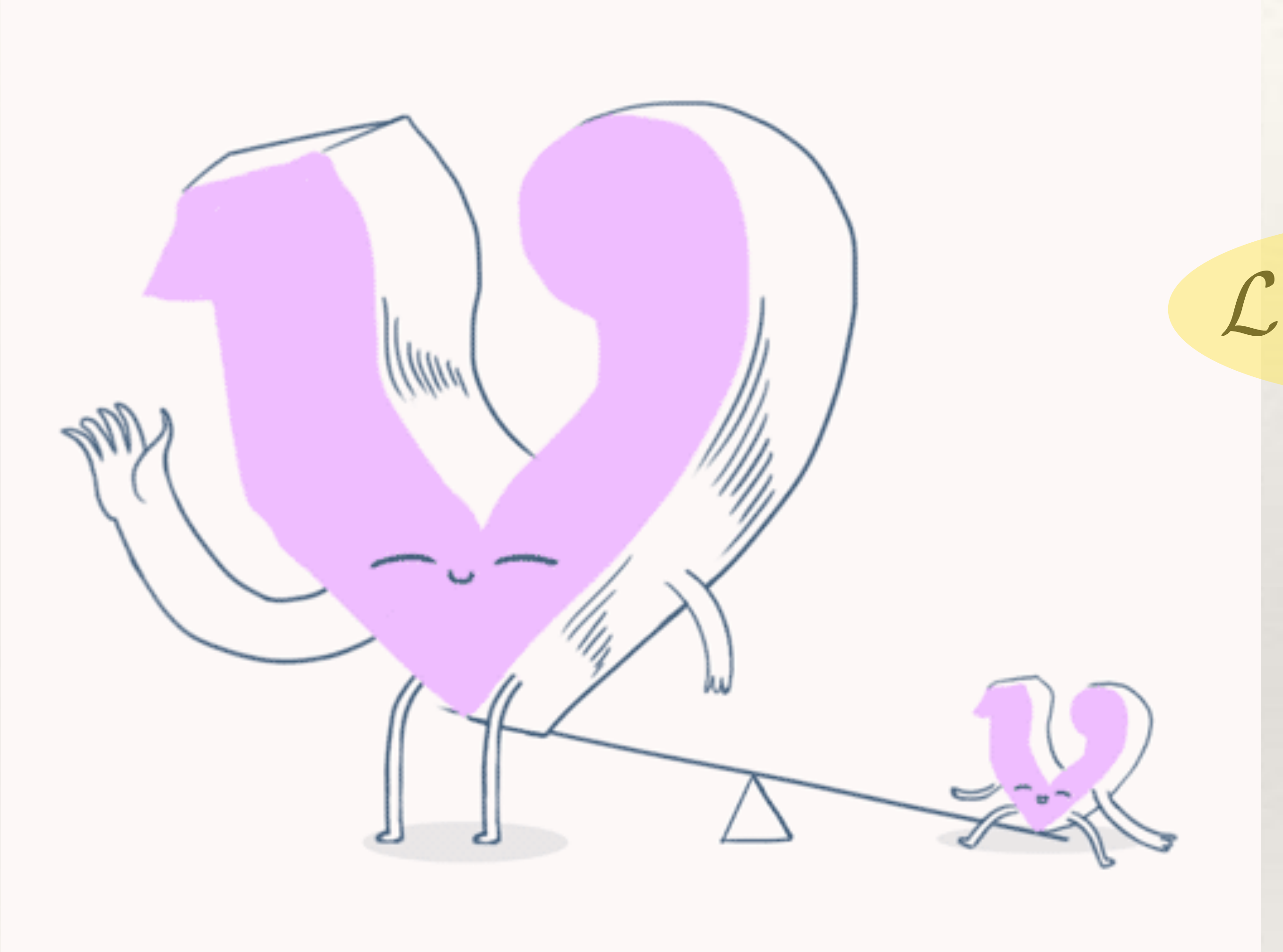

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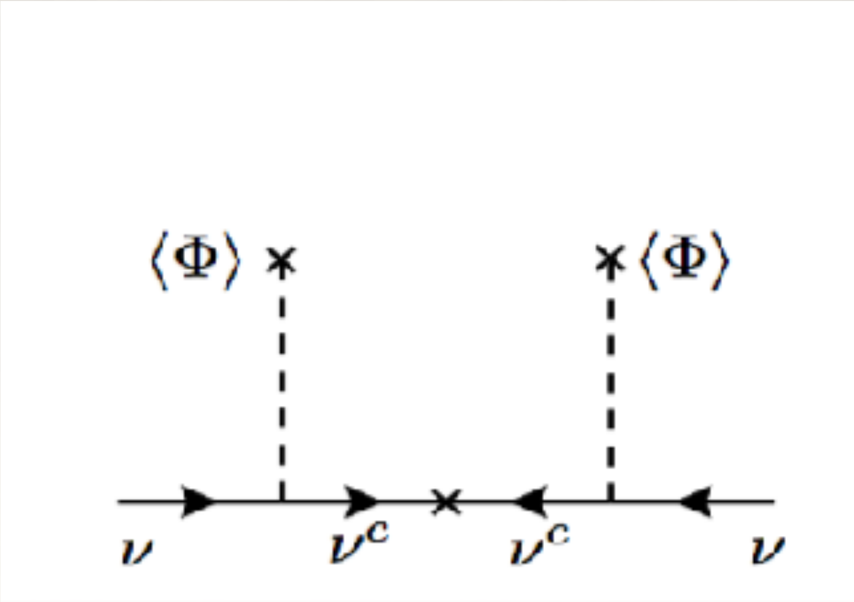
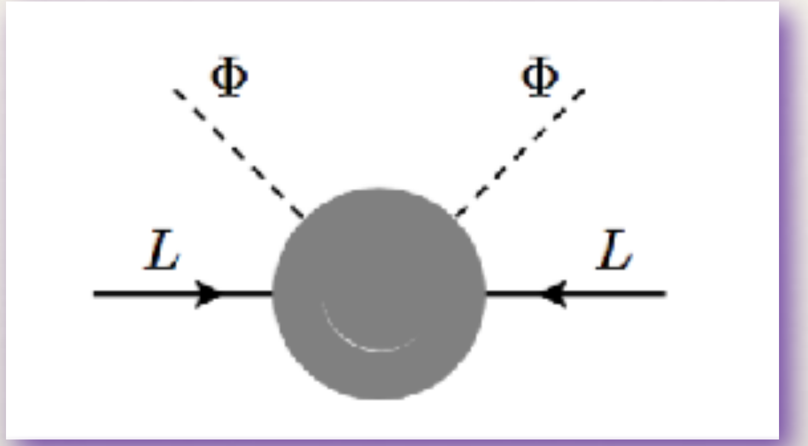


See-Saw

- **The simplest effective source of Majorana neutrino masses dim 5 Weinberg operator**



Weinberg, S. (1980)

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See-Saw

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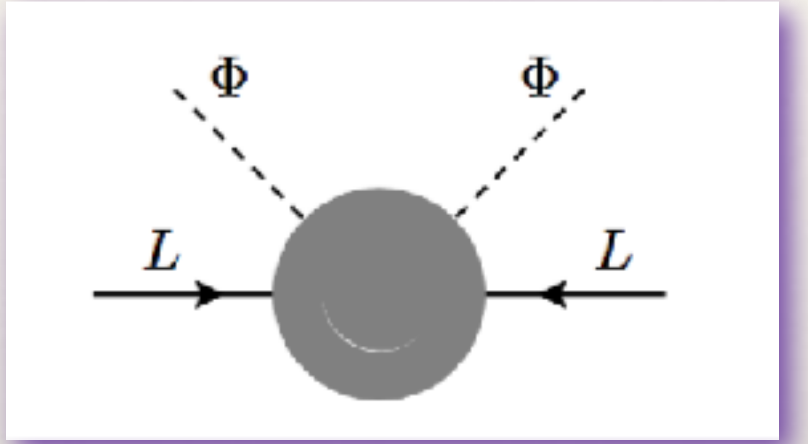

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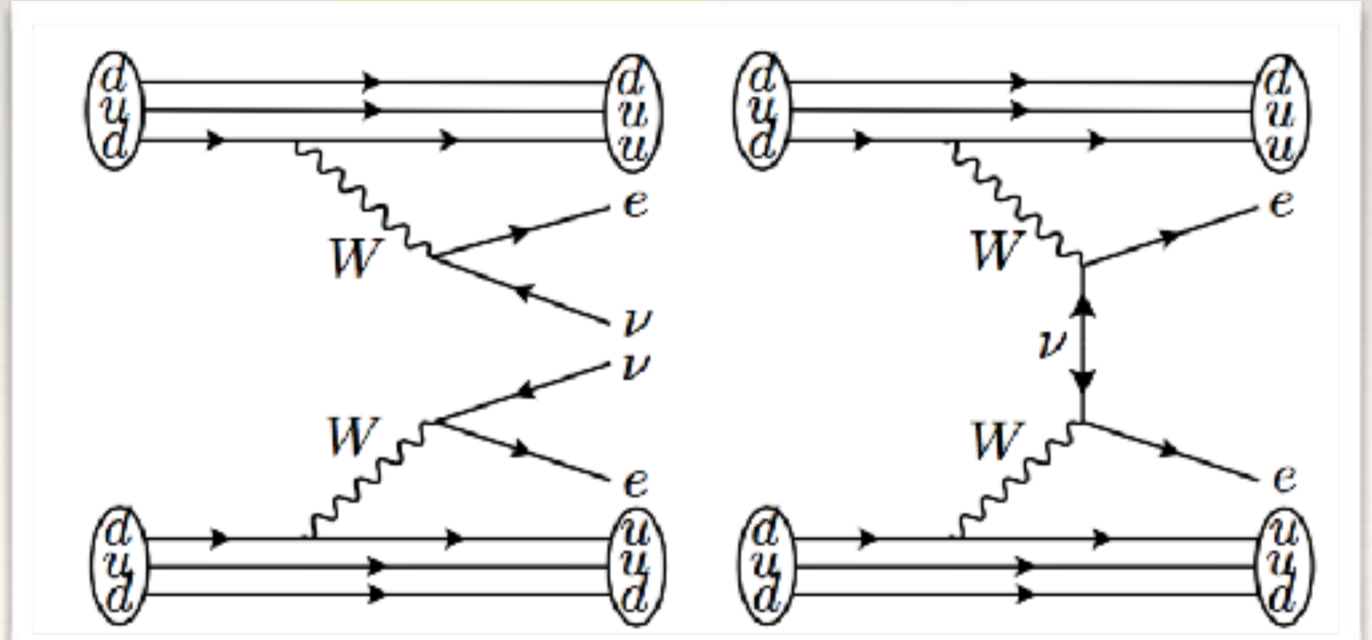
- **Implications?**

$$0\nu\beta\beta$$



UV-completion dim 5 operator

seesaw

- We have several possibilities SU(2) doublets L

$$2 \otimes 2 = 1 + 3$$

type I seesaw

LHN $\qquad 2 \otimes 2 \otimes 1$

type II seesaw

$L\Delta L$ $\qquad 2 \otimes 3 \otimes 2$

type III seesaw

$LH\Sigma$ $\qquad 2 \otimes 3 \otimes 2$

UV-completion dim 5 operator

seesaw

- We have several possibilities SU(2) doublets L

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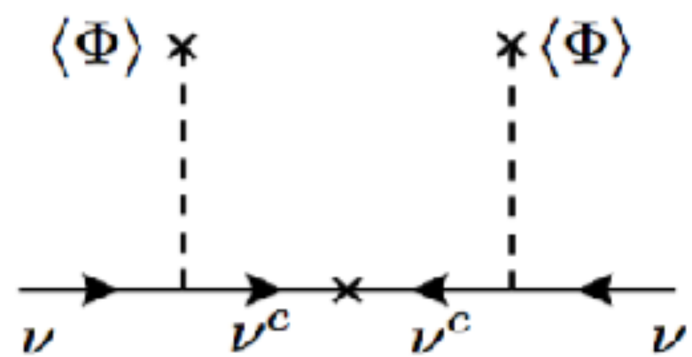

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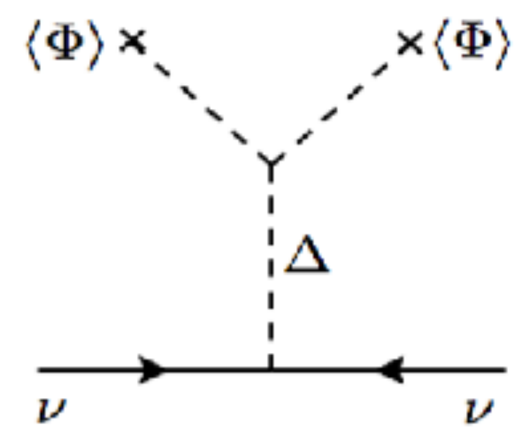

type II seesaw

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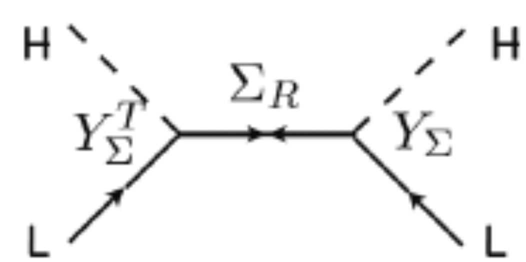
type III seesaw

$LH\Sigma \qquad 2 \otimes 3 \otimes 2$



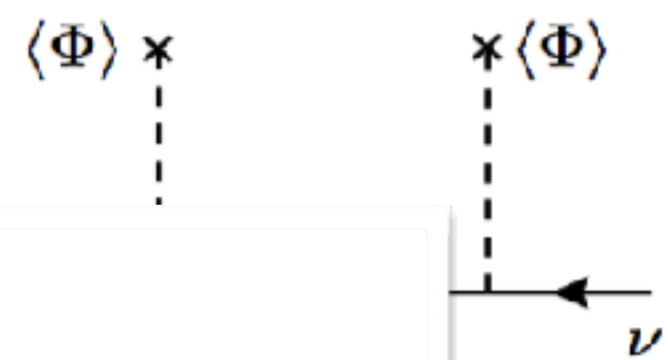
Type III

UV-completion dim 5 operator

seesaw

- We have several possibilities SU(2) doublets L

$$2 \otimes 2 = 1 + 3$$



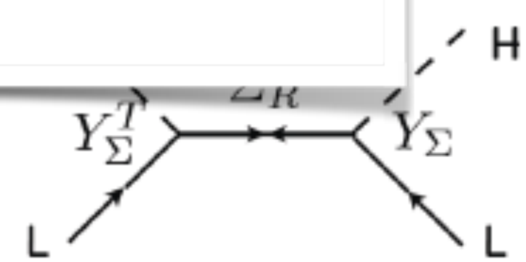
type I

type I

$$\mathcal{M}_\nu = \begin{bmatrix} M_1 & M_D \\ M_D^T & M_2 \end{bmatrix}$$

type II

$LH\Sigma$ $\qquad 2 \otimes 3 \otimes 2$



Type III

Flavour symmetries

FS has been used to reduce
# of Yukawa couplings

Correlations among observables
masses, mixings and CP phases

Sometimes predictions
such as TBM mixing

Flavour symmetries

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Sometimes predictions
such as TBM mixing

Texture Zeros to obtain Correlations

$$A_1: \begin{pmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}, \quad A_2: \begin{pmatrix} 0 & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}$$

$$B_1: \begin{pmatrix} X & X & 0 \\ X & 0 & X \\ 0 & X & X \end{pmatrix}, \quad B_2: \begin{pmatrix} X & 0 & X \\ 0 & X & X \\ X & X & 0 \end{pmatrix},$$

$$B_3: \begin{pmatrix} X & 0 & X \\ 0 & 0 & X \\ X & X & X \end{pmatrix}, \quad B_4: \begin{pmatrix} X & X & 0 \\ X & X & X \\ 0 & X & 0 \end{pmatrix},$$

$$C: \begin{pmatrix} X & X & X \\ X & 0 & X \\ X & X & 0 \end{pmatrix},$$

Frampton, Glashow, Marfatia

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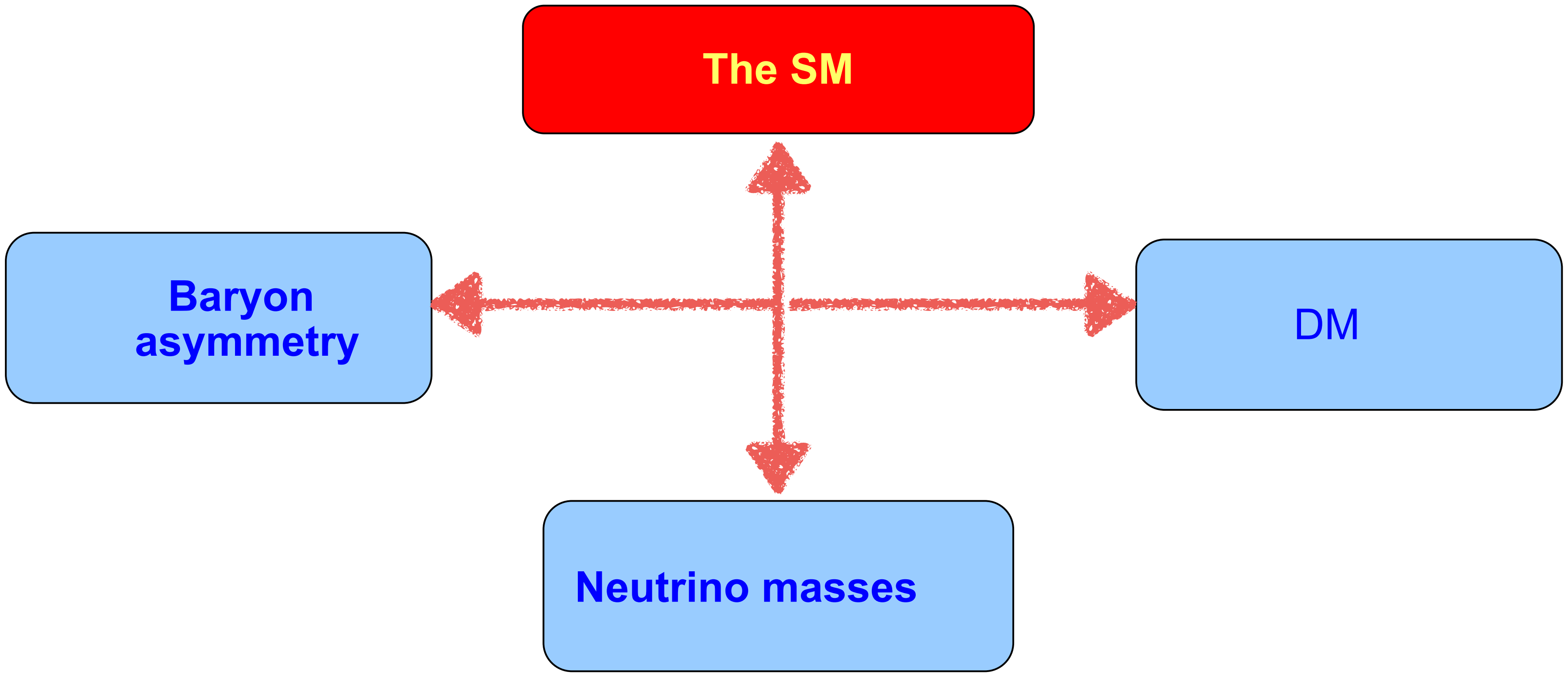
Frampton, Glashow, Marfatia

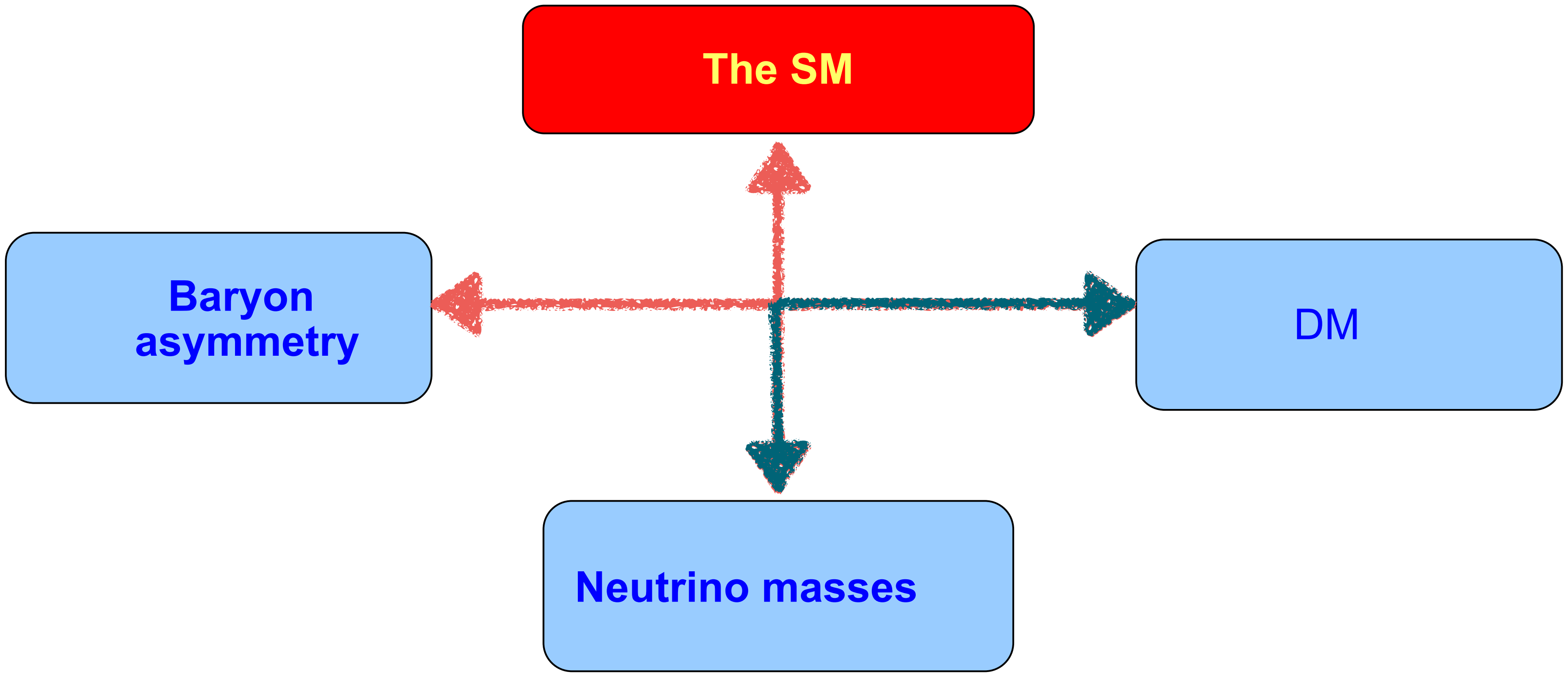
Connection of neutrinos with DM

The SM

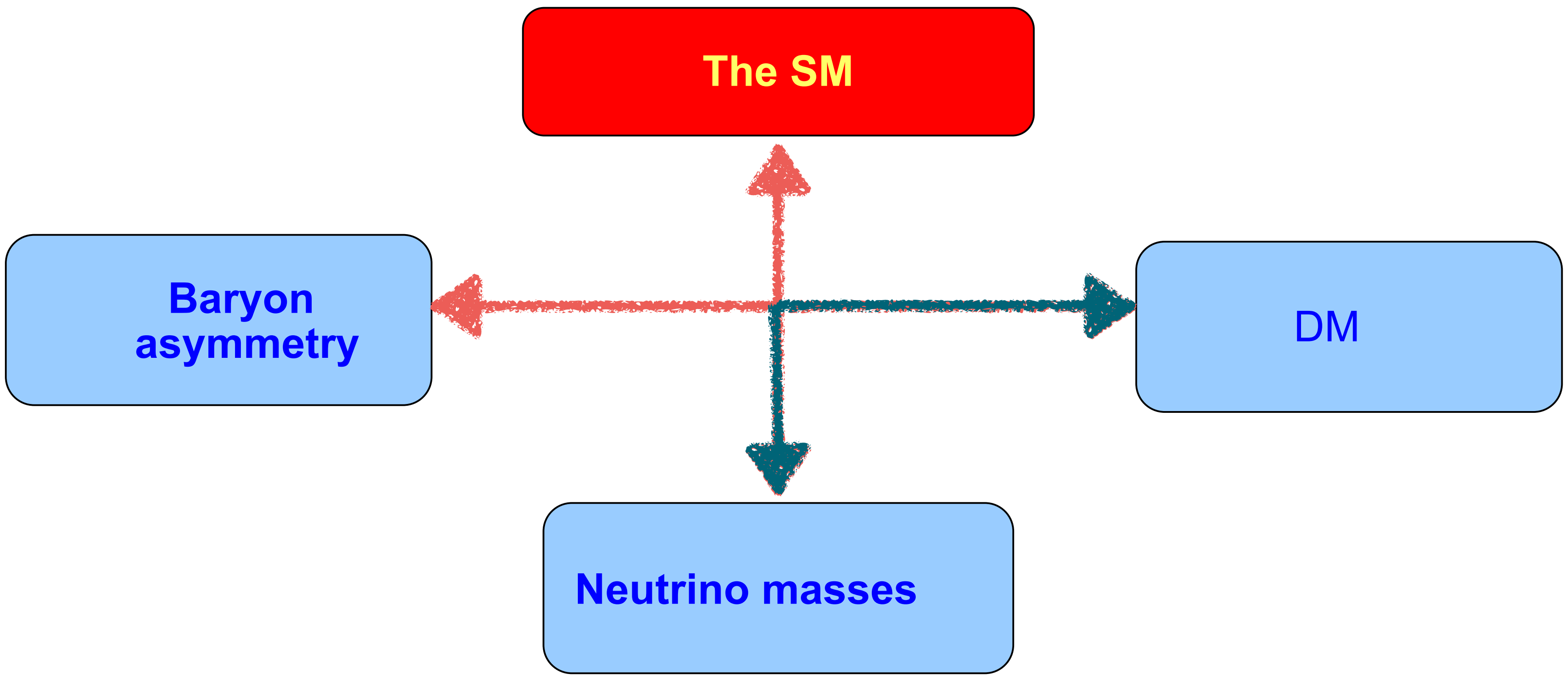
Connection of neutrinos with DM



Connection of neutrinos with DM



Connection of neutrinos with DM



Majoron

Inert+loops

DDM

loops with higher Higgs representations

KeV sterile neutrinos

etc...

Stability

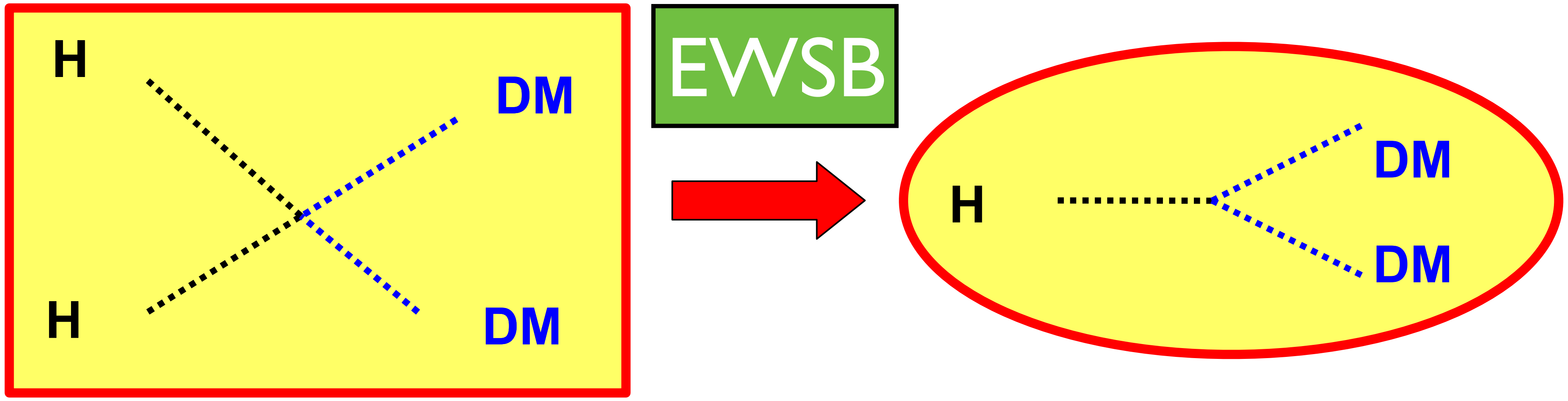
Symmetry

	SM	+	χ
Z_2	$+1$		-1

Stability

Symmetry

	SM	+	χ
Z_2	$+1$		-1



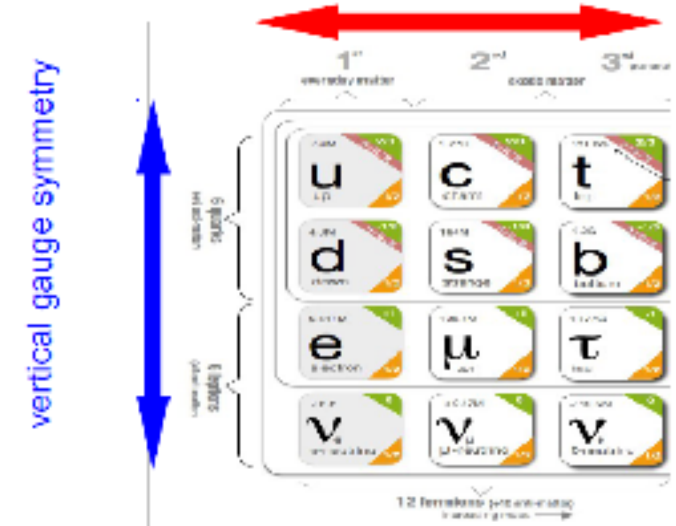
Higgs portal

Flavor symmetries

Frampton and Kephart, PRD64 (01)

order	groups
6	$S_3 \equiv D_3$
8	$D_4, Q = Q_4$
10	D_5
12	$D_6, Q_6, T \equiv A_4$
14	D_7
16	$D_8, Q_8, Z_2 \times D_4, Z_2 \times Q$
18	$D_9, Z_3 \times D_3$
20	D_{10}, Q_{10}
22	D_{11}
24	$D_{12}, Q_{12}, Z_2 \times D_6, Z_2 \times Q_6, Z_2 \times T, Z_3 \times D_4, Z_3 \times Q, Z_4 \times D_3, S_4$
26	D_{13}
28	D_{14}, Q_{14}
30	$D_{15}, D_5 \times Z_3, D_3 \times Z_5$

horizontal symmetry like *SU(3)* – *triplets*



Abelian, non abelian
continuous, discrete,
global, local

Z_N already in these symmetries

A4

Ma and Rajasekaran 2001
Babu, Ma, Valle 2003
Altarelli, Feruglio 2005
...

The generators are :

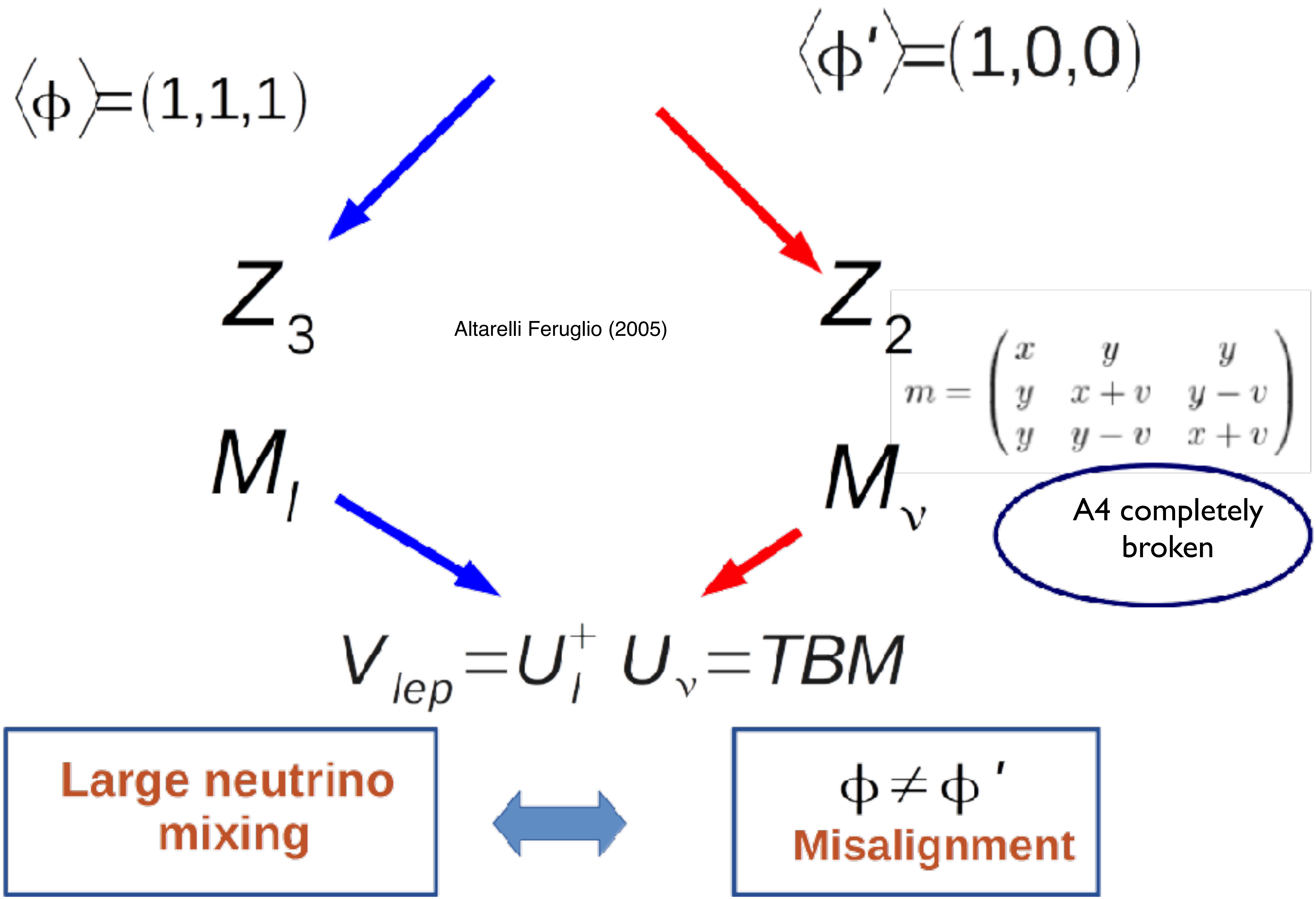
S and T $\qquad S^2 = T^3 = (ST)^3 = \mathcal{I}.$

$1,\ 1',\ 1''$ and 3

1	$S = 1$	$T = 1$
$1'$	$S = 1$	$T = e^{i4\pi/3} \equiv \omega^2$
$1''$	$S = 1$	$T = e^{i2\pi/3} \equiv \omega$

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad T = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$

A4 and TBM



$\langle\phi\rangle=(1,1,1)$
$\langle\phi'\rangle=(1,0,0)$
Z_3
Altarelli Feruglio (2005)
Z_2
$m = \begin{pmatrix} x & y & y \\ y & x+v & y-v \\ y & y-v & x+v \end{pmatrix}$
M_l
M_ν
A4 completely broken
$V_{lep}=U_l^+ U_\nu = TBM$
Large neutrino mixing
$\phi\neq\phi'$
Misalignment

How to use it to stabilise DM

Instead of **breaking A4** in two different directions

$$\langle\phi\rangle = (1,0,0)$$

Preserves "S" (Z_2)

~~$$\langle\phi\rangle = (1,1,1)$$~~

~~Preserves "T" (Z_3)~~

How to use it to stabilise DM

Instead of **breaking A4** in two different directions

$\langle \phi \rangle = (1, 0, 0)$

Preserves "S" (Z_2)

~~$\langle \phi \rangle = (1, 1, 1)$~~

~~Preserves "T" (Z_3)~~

No TBM, but Z2

→ DM Stability

The Discrete Dark Matter

- We need a non-abelian flavor group
- Scalar fields in a non-trivial irrep
- This scalar only couples with leptons
- not connected with quarks
- The vev of the scalar breaks the flavor into a Z_N subgroup of the FS
- This breaking dictates the Neutrino pheno

The model

SM + 3 Higgs SU(2) doublets , 4 right handed neutrinos

Hirsch, Morisi, Peinado and Valle
Phys. Rev. D 82, 116003 (2010)

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	H	η
$SU(2)$	2	2	2	1	1	1	1	1	2	2
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1	1	3

$\langle \eta^0_{2,3} \rangle = 0$

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

$\langle \eta^0_1 \rangle = v_\eta$

$\langle H^0 \rangle = v_h$

$$m_D = \begin{pmatrix} x_1 & 0 & 0 & y_1 \\ x_2 & 0 & 0 & 0 \\ x_3 & 0 & 0 & 0 \end{pmatrix}$$

$$M_R = \mathrm{diag}(M_1, M_1, M_1, M_2)$$

inert part

Rank 2 matrix

Neutrino Pheno

Scaling matrix,
Rodejohan and Mohapatra

$$\begin{pmatrix} y^2 & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{pmatrix} \rightarrow \quad m_3 = 0 \quad \begin{pmatrix} 0 \\ -c/b \\ 1 \end{pmatrix}$$

Inverse mass Hierarchy

$$\left\{ m_{ee} \sim 0.03 - 0.05\ eV \right\}$$

Neutrino Pheno

Scaling matrix,
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$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34±0.20	1.95–2.74	1.77–2.94
$\theta_{13}/^\circ$	8.8±0.4	8.0–9.5	7.7–9.9

Inverse mass Hierarchy

$$\{\, m_{ee} \sim 0.03 - 0.05\ eV \,\}$$

The path to θ_{13}

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Lets couple a scalar field with RH neutrinos

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Lets couple a scalar field with RH neutrinos

↓

This scalar field breaks the FS at the see-saw scale

The path to θ_{13}

Lets couple a scalar field with RH neutrinos

↓

This scalar field breaks the FS at the see-saw scale

↓

At EW we have a Z_2 (like in the inert case)

The model(s)

M. Lamprea and E. Peinado (2016)

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	N_5	H	η	ϕ
SU(2)	2	2	2	1	1	1	1	1	1	2	2	1
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1	$1'$	1	3	3

$$\langle\phi\rangle = (1,0,0)$$

$$A_4 \longrightarrow Z_2$$

In order to preserve the Z_2, only η_1 acquire vev

$$\mathcal{L}_{\rm Y}^{(\rm A)} = y_e L_e l_e^c H + y_\mu L_\mu l_\mu^c H + y_\tau L_\tau l_\tau^c H$$
$$+ y_1^\nu L_e [N_T\,\eta]_1 + y_2^\nu L_\mu [N_T\,\eta]_{1''} + y_3^\nu L_\tau [N_T\,\eta]_{1'} + y_4^\nu L_e\, N_4\, H + y_5^\nu L_\tau\, N_5\, H$$
$$+ M_1\, N_T N_T + M_2\, N_4 N_4 + y_1^N [N_T\,\phi]_{3_i} N_T + y_2^N [N_T\,\phi]_1 N_4 + y_3^N [N_T\,\phi]_{1''} N_5$$

Neutrino masses

M. Lamprea and E. Peinado (2016)

$$m_{\mathrm{D}}^{(\mathrm{A})} = \begin{pmatrix} y_1^\nu v_\eta & 0 & 0 & y_4^\nu v_h & 0 \\ y_2^\nu v_\eta & 0 & 0 & 0 & 0 \\ y_3^\nu v_\eta & 0 & 0 & 0 & y_5^\nu v_h \end{pmatrix}$$

$$M_{\mathrm{R}} = \begin{pmatrix} M_1 & 0 & 0 & y_2^N v_\phi & y_3^N v_\phi \\ 0 & M_1 & y_1^N v_\phi & 0 & 0 \\ 0 & y_1^N v_\phi & M_1 & 0 & 0 \\ y_2^N v_\phi & 0 & 0 & M_2 & 0 \\ y_3^N v_\phi & 0 & 0 & 0 & 0 \end{pmatrix}$$

Neutrino masses

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$$M_{\rm R} = \begin{pmatrix} M_1 & 0 & 0 & y_2^N v_\phi & y_3^N v_\phi \\ 0 & M_1 & y_1^N v_\phi & 0 & 0 \\ 0 & y_1^N v_\phi & M_1 & 0 & 0 \\ y_2^N v_\phi & 0 & 0 & M_2 & 0 \\ y_3^N v_\phi & 0 & 0 & 0 & 0 \end{pmatrix}$$

Effectively only 3 RHN participate in the see-saw

Neutrino masses

M. Lamprea and E. Peinado (2016)

$$m_D^{(A)} = \begin{pmatrix} y_1^\nu v_\eta & 0 & 0 & y_4^\nu v_h & 0 \\ y_2^\nu v_\eta & 0 & 0 & 0 & 0 \\ y_3^\nu v_\eta & 0 & 0 & 0 & y_5^\nu v_h \end{pmatrix}$$

$$M_R = \begin{pmatrix} M_1 & 0 & 0 & y_2^N v_\phi & y_3^N v_\phi \\ 0 & M_1 & y_1^N v_\phi & 0 & 0 \\ 0 & y_1^N v_\phi & M_1 & 0 & 0 \\ y_2^N v_\phi & 0 & 0 & M_2 & 0 \\ y_3^N v_\phi & 0 & 0 & 0 & 0 \end{pmatrix}$$

Effectively only 3 RHN participate in the see-saw

$$m_\nu^{(A)} \equiv \begin{pmatrix} a & 0 & b \\ 0 & 0 & c \\ b & c & d \end{pmatrix}$$

Two zero-texture B3

Frampton, Glashow ,Marfatia
Merle, Rodejohan
Xing, Fritsch
Ludl, Morisi, Peinado
Meroni, Meloni, Peinado
…

Neutrino masses

M. Lamprea and E. Peinado (2016)

$$m_{\mathrm{D}}^{(\mathrm{A})} = \begin{pmatrix} y_1^\nu v_\eta & 0 & 0 & y_4^\nu v_h & 0 \\ y_2^\nu v_\eta & 0 & 0 & 0 & 0 \\ y_3^\nu v_\eta & 0 & 0 & 0 & y_5^\nu v_h \end{pmatrix}$$

$$M_{\mathrm{R}} = \begin{pmatrix} M_1 & 0 & 0 & y_2^N v_\phi & y_3^N v_\phi \\ 0 & M_1 & y_1^N v_\phi & 0 & 0 \\ 0 & y_1^N v_\phi & M_1 & 0 & 0 \\ y_2^N v_\phi & 0 & 0 & M_2 & 0 \\ y_3^N v_\phi & 0 & 0 & 0 & 0 \end{pmatrix}$$

Effectively only 3 RHN participate in the see-saw

tex

If N5 is 1''

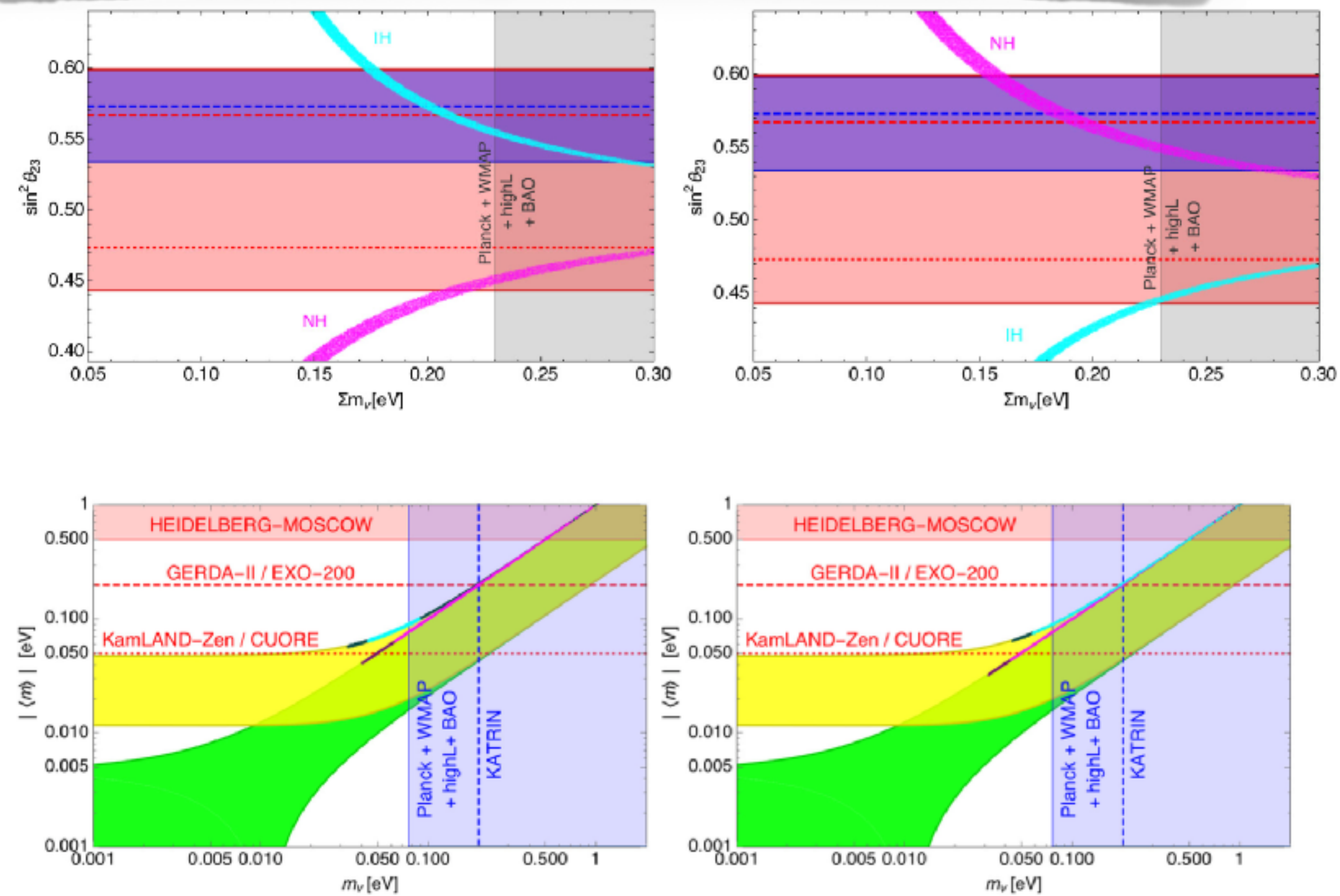
$$m_\nu^{(\mathrm{A})} \equiv \begin{pmatrix} a & 0 & b \\ 0 & 0 & c \\ b & c & d \end{pmatrix}$$

Ludl, Morisi, Peinado
Meroni, Meloni, Peinado
…

$$m_\nu^{(\mathrm{B})} \equiv \begin{pmatrix} a & b & 0 \\ b & d & c \\ 0 & c & 0 \end{pmatrix}$$

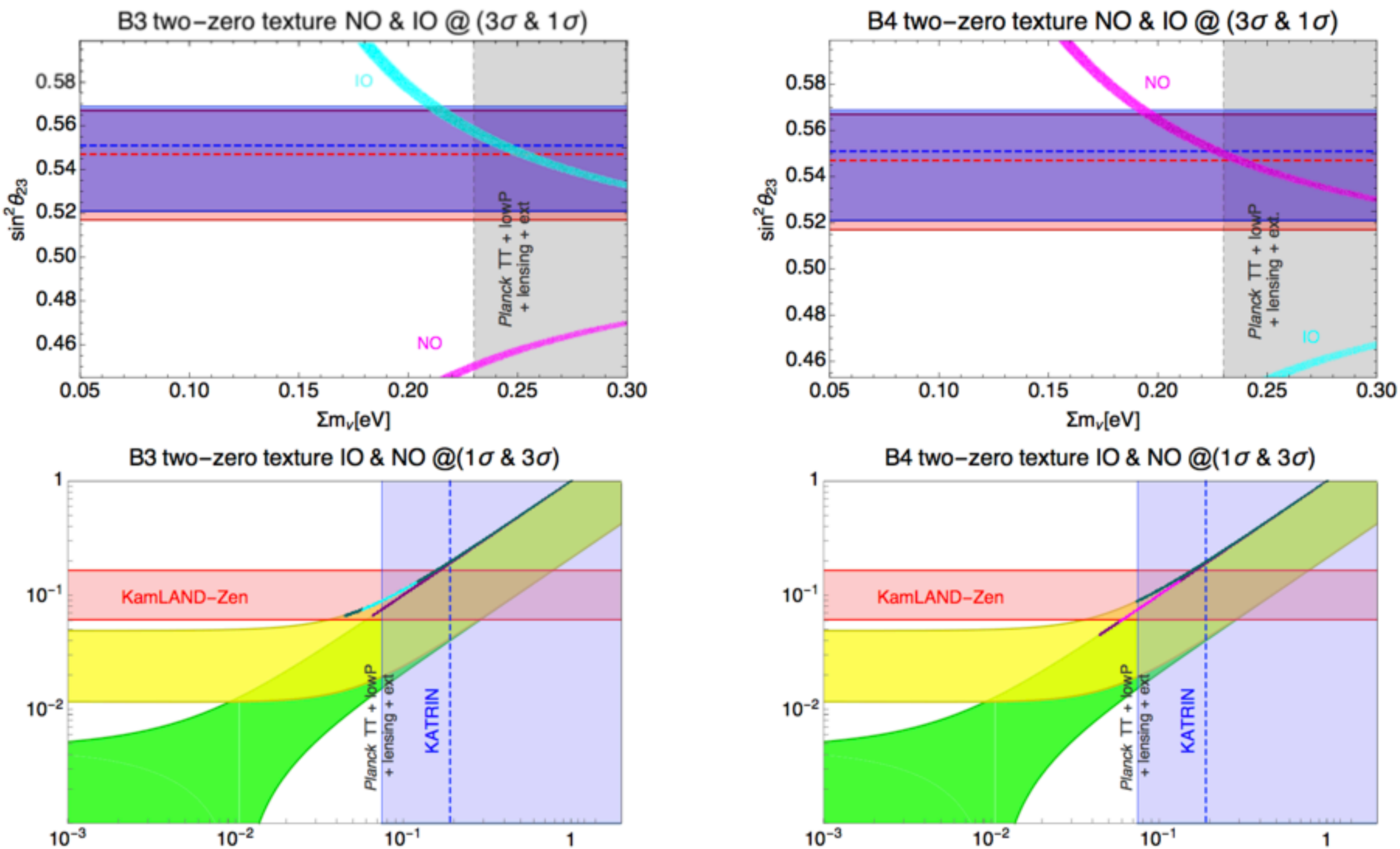
Neutrino Phenomenology

Data from D.V.Forero,M.Tortola and J.W.F.Valle,Phys.Rev.D90(2014)9,093006



Updated

de Salas, Forero, Ternes, Tortola, Valle (2018)



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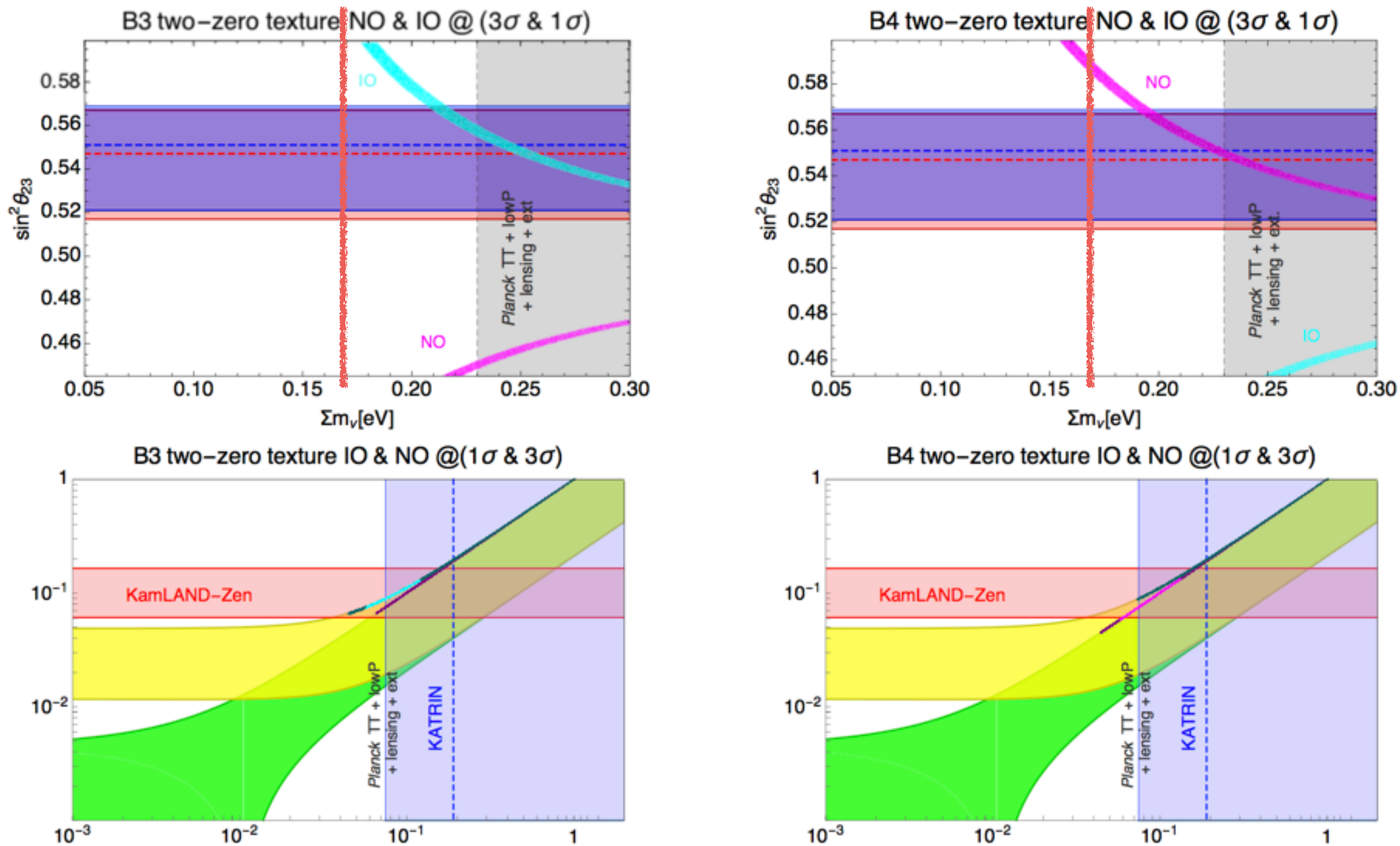

Summary

- Neutrino pheno "compatible" with DDM
- The atmospheric mixing angle correlates with neutrino masses
- Neutrinoless double beta decay lower bound also for NH
- Barion assymetry?

Thank you and
Let's the game begin!!!!!!!