Neutrino and dark matter phenomenology from an A_4 Discrete Dark Matter Model

Mario Lamprea

Institute of Physics, U. Mexico

Based on [Phys. Rev. D 94, 055007] and [in prep.]

in collaboration with E. Peinado

20th Planck Conference

Warsaw, May 25th 2017

Motivation

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: $\mathbf{3}$.

Motivation

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: $\mathbf{3}$.

Product rule:

$$\mathbf{1_1} \otimes \mathbf{1_1} = \mathbf{1_1},\quad \mathbf{1_2} \otimes \mathbf{1_2} = \mathbf{1_3},\quad \mathbf{1_3} \otimes \mathbf{1_3} = \mathbf{1_2},$$

$$\mathbf{1_1} \otimes \mathbf{1_2} = \mathbf{1_2},\quad \mathbf{1_1} \otimes \mathbf{1_3} = \mathbf{1_3},\quad \mathbf{1_2} \otimes \mathbf{1_3} = \mathbf{1_1},$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1_1} \oplus \mathbf{1_2} \oplus \mathbf{1_3} \oplus \mathbf{3} \oplus \mathbf{3}.$$

Motivation

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: $\mathbf{3}$.

Product rule:

$$\mathbf{1_1} \otimes \mathbf{1_1} = \mathbf{1_1},\quad \mathbf{1_2} \otimes \mathbf{1_2} = \mathbf{1_3},\quad \mathbf{1_3} \otimes \mathbf{1_3} = \mathbf{1_2},$$

$$\mathbf{1_1} \otimes \mathbf{1_2} = \mathbf{1_2},\quad \mathbf{1_1} \otimes \mathbf{1_3} = \mathbf{1_3},\quad \mathbf{1_2} \otimes \mathbf{1_3} = \mathbf{1_1},$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1_1} \oplus \mathbf{1_2} \oplus \mathbf{1_3} \oplus \mathbf{3} \oplus \mathbf{3}.$$

A_4 has two sub-groups Z_2, Z_3.

Two generators: $\boldsymbol{S}$, $\boldsymbol{T}$.

Motivation

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: $\mathbf{3}$.

Product rule:

$$\mathbf{1_1} \otimes \mathbf{1_1} = \mathbf{1_1},\quad \mathbf{1_2} \otimes \mathbf{1_2} = \mathbf{1_3},\quad \mathbf{1_3} \otimes \mathbf{1_3} = \mathbf{1_2},$$

$$\mathbf{1_1} \otimes \mathbf{1_2} = \mathbf{1_2},\quad \mathbf{1_1} \otimes \mathbf{1_3} = \mathbf{1_3},\quad \mathbf{1_2} \otimes \mathbf{1_3} = \mathbf{1_1},$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1_1} \oplus \mathbf{1_2} \oplus \mathbf{1_3} \oplus \mathbf{3} \oplus \mathbf{3}.$$

A_4 has two sub-groups Z_2, Z_3.

$$\boxed{A_4} \longrightarrow \boxed{Z_2}$$

Two generators: ***S***, ***T***.

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

Generators in the a *3 dim.* rep. (with ***S*** *real* and *diagonal*).

Motivation

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: $\mathbf{3}$.

Product rule:

$$\mathbf{1_1} \otimes \mathbf{1_1} = \mathbf{1_1}, \quad \mathbf{1_2} \otimes \mathbf{1_2} = \mathbf{1_3}, \quad \mathbf{1_3} \otimes \mathbf{1_3} = \mathbf{1_2},$$

$$\mathbf{1_1} \otimes \mathbf{1_2} = \mathbf{1_2}, \quad \mathbf{1_1} \otimes \mathbf{1_3} = \mathbf{1_3}, \quad \mathbf{1_2} \otimes \mathbf{1_3} = \mathbf{1_1},$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1_1} \oplus \mathbf{1_2} \oplus \mathbf{1_3} \oplus \mathbf{3} \oplus \mathbf{3}.$$

A_4 has two sub-groups Z_2, Z_3.

$$\begin{tikzcd} & \boxed{A_4} \arrow[dl] \arrow[dr] & \\ \boxed{Z_2} & & \boxed{Z_3} \end{tikzcd}$$

Two generators: ***S***, ***T***.

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

Generators in the a *3 dim.* rep. (with ***S*** *real* and *diagonal*).

Motivation

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: $\mathbf{3}$.

Product rule:

$$\mathbf{1_1} \otimes \mathbf{1_1} = \mathbf{1_1}, \quad \mathbf{1_2} \otimes \mathbf{1_2} = \mathbf{1_3}, \quad \mathbf{1_3} \otimes \mathbf{1_3} = \mathbf{1_2},$$

$$\mathbf{1_1} \otimes \mathbf{1_2} = \mathbf{1_2}, \quad \mathbf{1_1} \otimes \mathbf{1_3} = \mathbf{1_3}, \quad \mathbf{1_2} \otimes \mathbf{1_3} = \mathbf{1_1},$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1_1} \oplus \mathbf{1_2} \oplus \mathbf{1_3} \oplus \mathbf{3} \oplus \mathbf{3}.$$

A_4 has two sub-groups Z_2, Z_3.

$$\begin{tikzcd} & \boxed{A_4} \arrow[dl] \arrow[dr] & \\ \boxed{Z_2} & & \boxed{Z_3} \end{tikzcd}$$

Two generators: ***S***, ***T***.

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

Generators in the a *3 dim.* rep. (with ***S*** *real* and *diagonal*).

Motivation

Discrete Dark Matter Model: [M. Hirsch, *et al*. ‘10]

Non-Abelian discrete flavour symmetry breaking into one of its subgroups, by means of EWSB, accounts for the neutrino masses and mixing and dark matter stability.

A_4 DDM models: [M. Hirsch *et al*. 10’, D. Meloni, *et al*. ‘10] Charged leptons diagonal. Light neutrino masses and mixings via type I Seesaw. DM Candidate.

Interesting DM phenomenology [M. S Boucena, *et al*. ’11].

Motivation

Discrete Dark Matter Model: [M. Hirsch, *et al.* ‘10]

Non-Abelian discrete flavour symmetry breaking into one of its subgroups, by means of EWSB, accounts for the neutrino masses and mixing and dark matter stability.

A_4 DDM models: [M. Hirsch *et al.* 10’, D. Meloni, *et al.* ‘10] Charged leptons diagonal. Light neutrino masses and mixings via type I Seesaw. DM Candidate.

Interesting DM phenomenology [M. S Boucena, *et al.* ’11].

Motivation

Discrete Dark Matter Model: [M. Hirsch, *et al*. ‘10]

Non-Abelian discrete flavour symmetry breaking into one of its subgroups, by means of EWSB, accounts for the neutrino masses and mixing and dark matter stability.

A_4 DDM models: [M. Hirsch *et al*. 10’, D. Meloni, *et al*. ‘10] Charged leptons diagonal. Light neutrino masses and mixings via type I Seesaw. DM Candidate.

Interesting DM phenomenology [M. S Boucena, *et al*. ’11].

The Model

Particle assignments

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

	H	η	ϕ
SU(2)	2	2	1
A_4	1	3	3

The Model

Particle assignments

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

SM

	H	η	ϕ
SU(2)	2	2	1
A_4	1	3	3

The Model

Particle assignments

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

New particles

	H	η	ϕ
SU(2)	2	2	1
A_4	1	3	3

The Model

Particle assignments

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

	H	η	ϕ
SU(2)	2	2	1
A_4	1	3	3

The Model

Particle assignments

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

	H	η	ϕ
SU(2)	2	2	1
A_4	1	3	3

$$N_T = \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}$$

The Model

Particle assignments

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

	H	η	ϕ
SU(2)	2	2	1
A_4	1	3	3

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$$

$$\eta = \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix}$$

The Model

Particle assignments

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	N_5
SU(2)	2	2	2	1	1	1	1	1	1
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1	$\boxed{1'}$

$1''$

	H	η	ϕ
SU(2)	2	2	1
A_4	1	3	3

Another model, analogous pheno.

The Model

Symmetry breaking

$\boxed{A_4}$

The Model

Symmetry breaking

Flavour symmetry breaking (at a scale close to the seesaw scale)

A_4 $\downarrow$ **Z_2**

*Seesaw scale

Type I Seesaw

Induced by the flavon, ϕ, VEV alignment:

$$\langle\phi_1\rangle = v_\phi \neq 0, \quad \langle\phi_{2,3}\rangle = 0.$$

Let ***S*** (Z_2) invariant.

The Model

Symmetry breaking

Flavour symmetry breaking (at a scale close to the seesaw scale)

*Seesaw scale

Type I Seesaw

A_4

Induced by the flavon, ϕ, VEV alignment:

$$\langle \phi_1 \rangle = v_\phi \neq 0, \quad \langle \phi_{2,3} \rangle = 0.$$

Let ***S*** (Z_2) invariant.

Z_2

Effective Z_2 potential at the EW scale. (Flavon dynamics integrated out)

EWSB

Scalar fields, ***H*** and $\eta_{1,2,3}$, VEVs alignments:

$$\langle H^0 \rangle = v_h \neq 0, \quad \langle \eta_1^0 \rangle = v_\eta \neq 0, \quad \langle \eta_{2,3}^0 \rangle = 0$$

The Model

The Yukawa Lagrangian

Quarks are singlets: $Q_L q_R H$

$$\begin{aligned}\mathcal{L}_{\rm Y}^{(\rm A)} &= y_e L_e l_e^c H + y_\mu L_\mu l_\mu^c H + y_\tau L_\tau l_\tau^c H \\ &+ y_1^\nu L_e [N_T\,\eta]_1 + y_2^\nu L_\mu [N_T\,\eta]_{1''} + y_3^\nu L_\tau [N_T\,\eta]_{1'} + y_4^\nu L_e\, N_4\, H + y_5^\nu L_\tau\, N_5\, H \\ &+ M_1\, N_T N_T + M_2\, N_4 N_4 + y_1^N [N_T\,\phi]_3 N_T + y_2^N [N_T\,\phi]_1 N_4 + y_3^N [N_T\,\phi]_{1''} N_5 + h.c.\end{aligned}$$

Diagonal mass matrix for charged leptons.

Mixing only from Neutrinos (in $\mathbf{Z}_2$ even sector)

The Model

The Yukawa Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\mathrm{Y}}^{(\mathrm{A})} = & \boxed{y_e L_e l_e^c H + y_\mu L_\mu l_\mu^c H + y_\tau L_\tau l_\tau^c H} \\
& + y_1^\nu L_e [N_T\,\eta]_1 + y_2^\nu L_\mu [N_T\,\eta]_{1''} + y_3^\nu L_\tau [N_T\,\eta]_{1'} + y_4^\nu L_e\, N_4\, H + y_5^\nu L_\tau\, N_5\, H \\
& + M_1\, N_T N_T + M_2\, N_4 N_4 + y_1^N [N_T\,\phi]_3 N_T + y_2^N [N_T\,\phi]_1 N_4 + y_3^N [N_T\,\phi]_{1''} N_5 + h.c.
\end{aligned}
$$

Diagonal mass matrix for charged leptons.

Mixing only from Neutrinos (in Z_2 even sector)

The Model

The Yukawa Lagrangian

$$\mathcal{L}_{\mathrm{Y}}^{(\mathrm{A})} = y_e L_e l_e^c H + y_\mu L_\mu l_\mu^c H + y_\tau L_\tau l_\tau^c H$$
$$\boxed{\begin{aligned}&+ y_1^\nu L_e [N_T\,\eta]_1 + y_2^\nu L_\mu [N_T\,\eta]_{1''} + y_3^\nu L_\tau [N_T\,\eta]_{1'} + y_4^\nu L_e\, N_4\, H + y_5^\nu L_\tau\, N_5\, H \\ &+ M_1\, N_T N_T + M_2\, N_4 N_4 + y_1^N [N_T\,\phi]_3 N_T + y_2^N [N_T\,\phi]_1 N_4 + y_3^N [N_T\,\phi]_{1''} N_5 + h.c.\end{aligned}}$$

Diagonal mass matrix for charged leptons.

Mixing only from Neutrinos (in $\mathbf{Z}_2$ even sector)

The Model

The Z_2 effective potential (at the EW Scale):

$$
\begin{aligned}
V = {} & \mu_1^2\left(\eta_1^\dagger\eta_1\right) + \mu_2^2\left(h^\dagger h\right) + \mu_3^2\left(h^\dagger\eta_1 + \eta_1^\dagger h\right) + \mu_4^2\left(\eta_2^\dagger\eta_2 + \eta_3^\dagger\eta_3\right) + \mu_5^2\left(\eta_2^\dagger\eta_3 + \eta_3^\dagger\eta_2\right) \\
& + \lambda_1\left((\eta_1^\dagger\eta_1)^2 + (\eta_2^\dagger\eta_2)^2 + (\eta_3^\dagger\eta_3)^2\right) + \lambda_2\left(h^\dagger h\right)^2 \\
& + \lambda_3\left(\eta_1^\dagger\eta_1\,\eta_2^\dagger\eta_2 + \eta_1^\dagger\eta_1\,\eta_3^\dagger\eta_3 + \eta_2^\dagger\eta_2\,\eta_3^\dagger\eta_3\right) \\
& + \lambda_4\left(h^\dagger h\right)\left(\eta_1^\dagger\eta_1 + \eta_2^\dagger\eta_2 + \eta_3^\dagger\eta_3\right) \\
& + \lambda_5\left(\eta_2^\dagger\eta_1\,\eta_1^\dagger\eta_2 + \eta_3^\dagger\eta_1\,\eta_1^\dagger\eta_3 + \eta_3^\dagger\eta_2\,\eta_2^\dagger\eta_3\right) \\
& + \lambda_6\left(\eta_1^\dagger h\,h^\dagger\eta_1 + \eta_2^\dagger h\,h^\dagger\eta_2 + \eta_3^\dagger h\,h^\dagger\eta_3\right) \\
& + \lambda_7\left((\eta_3^\dagger\eta_1)^2 + (\eta_1^\dagger\eta_2)^2 + (\eta_2^\dagger\eta_3)^2\right) \\
& + \lambda_7^*\left((\eta_2^\dagger\eta_1)^2 + (\eta_3^\dagger\eta_2)^2 + (\eta_1^\dagger\eta_3)^2\right) \\
& + \lambda_8\left((\eta_1^\dagger h)^2 + (\eta_2^\dagger h)^2 + (\eta_3^\dagger h)^2\right) \\
& + \lambda_8^*\left((h^\dagger\eta_1)^2 + (h^\dagger\eta_2)^2 + (h^\dagger\eta_3)^2\right) \\
& + \lambda_9\left(\eta_2^\dagger\eta_3\eta_1^\dagger h + \eta_3^\dagger\eta_1\eta_2^\dagger h + \eta_1^\dagger\eta_2\eta_3^\dagger h\right) \\
& + \lambda_9^*\left(\eta_3^\dagger\eta_2 h^\dagger\eta_1 + \eta_1^\dagger\eta_3 h^\dagger\eta_2 + \eta_2^\dagger\eta_1 h^\dagger\eta_3\right) \\
& + \lambda_{10}\left(\eta_3^\dagger\eta_2\,\eta_1^\dagger h + \eta_1^\dagger\eta_3\,\eta_2^\dagger h + \eta_2^\dagger\eta_1\,\eta_3^\dagger h\right) \\
& + \lambda_{10}^*\left(\eta_2^\dagger\eta_3\,h^\dagger\eta_1 + \eta_3^\dagger\eta_1\,h^\dagger\eta_2 + \eta_1^\dagger\eta_2\,h^\dagger\eta_3\right)
\end{aligned}
$$

10 couplings and 5 μ-terms.

The Model

The Z_2 effective potential (at the EW Scale):

$$
\begin{aligned}
V = \;& \boxed{\mu_1^2 \left(\eta_1^\dagger \eta_1\right)} + \mu_2^2 \left(h^\dagger h\right) + \boxed{\mu_3^2 \left(h^\dagger \eta_1 + \eta_1^\dagger h\right)} + \boxed{\mu_4^2 \left(\eta_2^\dagger \eta_2 + \eta_3^\dagger \eta_3\right)} + \boxed{\mu_5^2 \left(\eta_2^\dagger \eta_3 + \eta_3^\dagger \eta_2\right)} \\
&+ \lambda_1 \left((\eta_1^\dagger \eta_1)^2 + (\eta_2^\dagger \eta_2)^2 + (\eta_3^\dagger \eta_3)^2\right) + \lambda_2 \left(h^\dagger h\right)^2 \\
&+ \lambda_3 \left(\eta_1^\dagger \eta_1 \, \eta_2^\dagger \eta_2 + \eta_1^\dagger \eta_1 \, \eta_3^\dagger \eta_3 + \eta_2^\dagger \eta_2 \, \eta_3^\dagger \eta_3\right) \\
&+ \lambda_4 \left(h^\dagger h\right) \left(\eta_1^\dagger \eta_1 + \eta_2^\dagger \eta_2 + \eta_3^\dagger \eta_3\right) \\
&+ \lambda_5 \left(\eta_2^\dagger \eta_1 \, \eta_1^\dagger \eta_2 + \eta_3^\dagger \eta_1 \, \eta_1^\dagger \eta_3 + \eta_3^\dagger \eta_2 \, \eta_2^\dagger \eta_3\right) \\
&+ \lambda_6 \left(\eta_1^\dagger h \, h^\dagger \eta_1 + \eta_2^\dagger h \, h^\dagger \eta_2 + \eta_3^\dagger h \, h^\dagger \eta_3\right) \\
&+ \lambda_7 \left((\eta_3^\dagger \eta_1)^2 + (\eta_1^\dagger \eta_2)^2 + (\eta_2^\dagger \eta_3)^2\right) \\
&+ \lambda_7^* \left((\eta_2^\dagger \eta_1)^2 + (\eta_3^\dagger \eta_2)^2 + (\eta_1^\dagger \eta_3)^2\right) \\
&+ \lambda_8 \left((\eta_1^\dagger h)^2 + (\eta_2^\dagger h)^2 + (\eta_3^\dagger h)^2\right) \\
&+ \lambda_8^* \left((h^\dagger \eta_1)^2 + (h^\dagger \eta_2)^2 + (h^\dagger \eta_3)^2\right) \\
&+ \lambda_9 \left(\eta_2^\dagger \eta_3 \eta_1^\dagger h + \eta_3^\dagger \eta_1 \eta_2^\dagger h + \eta_1^\dagger \eta_2 \eta_3^\dagger h\right) \\
&+ \lambda_9^* \left(\eta_3^\dagger \eta_2 h^\dagger \eta_1 + \eta_1^\dagger \eta_3 h^\dagger \eta_2 + \eta_2^\dagger \eta_1 h^\dagger \eta_3\right) \\
&+ \lambda_{10} \left(\eta_3^\dagger \eta_2 \, \eta_1^\dagger h + \eta_1^\dagger \eta_3 \, \eta_2^\dagger h + \eta_2^\dagger \eta_1 \, \eta_3^\dagger h\right) \\
&+ \lambda_{10}^* \left(\eta_2^\dagger \eta_3 \, h^\dagger \eta_1 + \eta_3^\dagger \eta_1 \, h^\dagger \eta_2 + \eta_1^\dagger \eta_2 \, h^\dagger \eta_3\right)
\end{aligned}
$$

New μ- terms appear due to **ϕ** vev

10 couplings and 5 μ-terms.

The Model

The Z_2 effective potential (at the EW Scale):

$$
\begin{aligned}
V = {} & \mu_1^2 \left(\eta_1^\dagger \eta_1\right) + \mu_2^2 \left(h^\dagger h\right) + \mu_3^2 \left(h^\dagger \eta_1 + \eta_1^\dagger h\right) + \mu_4^2 \left(\eta_2^\dagger \eta_2 + \eta_3^\dagger \eta_3\right) + \mu_5^2 \left(\eta_2^\dagger \eta_3 + \eta_3^\dagger \eta_2\right) \\
& + \lambda_1 \left((\eta_1^\dagger \eta_1)^2 + (\eta_2^\dagger \eta_2)^2 + (\eta_3^\dagger \eta_3)^2\right) + \lambda_2 \left(h^\dagger h\right)^2 \\
& + \lambda_3 \left(\eta_1^\dagger \eta_1 \, \eta_2^\dagger \eta_2 + \eta_1^\dagger \eta_1 \, \eta_3^\dagger \eta_3 + \eta_2^\dagger \eta_2 \, \eta_3^\dagger \eta_3\right) \\
& + \lambda_4 \left(h^\dagger h\right) \left(\eta_1^\dagger \eta_1 + \eta_2^\dagger \eta_2 + \eta_3^\dagger \eta_3\right) \\
& + \lambda_5 \left(\eta_2^\dagger \eta_1 \, \eta_1^\dagger \eta_2 + \eta_3^\dagger \eta_1 \, \eta_1^\dagger \eta_3 + \eta_3^\dagger \eta_2 \, \eta_2^\dagger \eta_3\right) \\
& + \lambda_6 \left(\eta_1^\dagger h \, h^\dagger \eta_1 + \eta_2^\dagger h \, h^\dagger \eta_2 + \eta_3^\dagger h \, h^\dagger \eta_3\right) \\
& + \lambda_7 \left((\eta_3^\dagger \eta_1)^2 + (\eta_1^\dagger \eta_2)^2 + (\eta_2^\dagger \eta_3)^2\right) \\
& + \lambda_7^* \left((\eta_2^\dagger \eta_1)^2 + (\eta_3^\dagger \eta_2)^2 + (\eta_1^\dagger \eta_3)^2\right) \\
& + \lambda_8 \left((\eta_1^\dagger h)^2 + (\eta_2^\dagger h)^2 + (\eta_3^\dagger h)^2\right) \\
& + \lambda_8^* \left((h^\dagger \eta_1)^2 + (h^\dagger \eta_2)^2 + (h^\dagger \eta_3)^2\right) \\
& + \lambda_9 \left(\eta_2^\dagger \eta_3 \eta_1^\dagger h + \eta_3^\dagger \eta_1 \eta_2^\dagger h + \eta_1^\dagger \eta_2 \eta_3^\dagger h\right) \\
& + \lambda_9^* \left(\eta_3^\dagger \eta_2 h^\dagger \eta_1 + \eta_1^\dagger \eta_3 h^\dagger \eta_2 + \eta_2^\dagger \eta_1 h^\dagger \eta_3\right) \\
& + \lambda_{10} \left(\eta_3^\dagger \eta_2 \, \eta_1^\dagger h + \eta_1^\dagger \eta_3 \, \eta_2^\dagger h + \eta_2^\dagger \eta_1 \, \eta_3^\dagger h\right) \\
& + \lambda_{10}^* \left(\eta_2^\dagger \eta_3 \, h^\dagger \eta_1 + \eta_3^\dagger \eta_1 \, h^\dagger \eta_2 + \eta_1^\dagger \eta_2 \, h^\dagger \eta_3\right)
\end{aligned}
$$

Mixing between:
h, η_1 (*Z_2 even*)
η_2, η_3 (*Z_2 odd*)

The Model

Scalar mass spectrum

$$M_h^2 = \frac{2v_h^3\lambda_2 - \mu_3^2 v_\eta}{v_h}\cos(\alpha)^2 + \frac{2v_\eta^3\lambda_1 - \mu_3^2 v_h}{v_\eta}\sin(\alpha)^2 + \left(\mu_3^2 + v_h v_\eta L\right)\sin(2\alpha),$$

$$M_{\eta_1}^2 = \frac{2v_h^3\lambda_2 - \mu_3^2 v_\eta}{v_h}\cos(\alpha)^2 + \frac{2v_\eta^3\lambda_1 - \mu_3^2 v_h}{v_\eta}\sin(\alpha)^2 - \left(\mu_3^2 + v_h v_\eta L\right)\sin(2\alpha),$$

$$M_{A_1}^2 = -\frac{\left(v_h\cos(\alpha) + v_\eta\sin(\alpha)\right)^2\left(\mu_3^2 + 2v_h v_\eta\lambda_8\right)}{v_h v_\eta},$$

$$M_{\eta_1^+}^2 = -\frac{\left(v_h\cos(\alpha) + v_\eta\sin(\alpha)\right)^2\left(\mu_3^2 + 2v_h v_\eta O\right)}{v_h v_\eta},$$

$$M_{\eta_2}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K + v_h^2 L + \left(2\mu_5^2 + 3v_\eta v_h M\right)\sin(2\alpha)\right),$$

$$M_{\eta_3}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K + v_h^2 L - \left(2\mu_5^2 + 3v_\eta v_h M\right)\sin(2\alpha)\right),$$

$$M_{A_2}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K' + v_h^2 L' + \left(2\mu_5^2 + v_h v_\eta M\right)\sin(2\alpha)\right),$$

$$M_{A_3}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K' + v_h^2 L' - \left(2\mu_5^2 + v_h v_\eta M\right)\sin(2\alpha)\right),$$

$$M_{\eta_2^+}^2 = \frac{1}{2}\left(2\mu_4^2 + \lambda_3 v_\eta^2 + \lambda_4 v_h^2 + (2\mu_5^2 + 2v_\eta v_h M)\sin(2\alpha)\right),$$

$$M_{\eta_3^+}^2 = \frac{1}{2}\left(2\mu_4^2 + \lambda_3 v_\eta^2 + \lambda_4 v_h^2 - (2\mu_5^2 + 2v_\eta v_h M)\sin(2\alpha)\right).$$

$$K = \lambda_3 + \lambda_5 + 2\lambda_7, \quad K' = \lambda_3 + \lambda_5 - 2\lambda_7,$$
$$L = \lambda_4 + \lambda_6 + 2\lambda_8, \quad L' = \lambda_4 + \lambda_6 - 2\lambda_8,$$
$$M = \lambda_9 + \lambda_{10}, \quad O = \lambda_6 + 2\lambda_8.$$

The Model

Scalar mass spectrum

$$M_h^2 = \frac{2v_h^3\lambda_2 - \mu_3^2 v_\eta}{v_h}\cos(\alpha)^2 + \frac{2v_\eta^3\lambda_1 - \mu_3^2 v_h}{v_\eta}\sin(\alpha)^2 + \left(\mu_3^2 + v_h v_\eta L\right)\sin(2\alpha),$$

$$M_{\eta_1}^2 = \frac{2v_h^3\lambda_2 - \mu_3^2 v_\eta}{v_h}\cos(\alpha)^2 + \frac{2v_\eta^3\lambda_1 - \mu_3^2 v_h}{v_\eta}\sin(\alpha)^2 - \left(\mu_3^2 + v_h v_\eta L\right)\sin(2\alpha),$$

$$M_{A_1}^2 = -\frac{\left(v_h\cos(\alpha) + v_\eta\sin(\alpha)\right)^2\left(\mu_3^2 + 2v_h v_\eta\lambda_8\right)}{v_h v_\eta},$$

$$M_{\eta_1^+}^2 = -\frac{\left(v_h\cos(\alpha) + v_\eta\sin(\alpha)\right)^2\left(\mu_3^2 + 2v_h v_\eta O\right)}{v_h v_\eta},$$

Z_2 even (2HDM)

$$M_{\eta_2}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K + v_h^2 L + \left(2\mu_5^2 + 3v_\eta v_h M\right)\sin(2\alpha)\right),$$

$$M_{\eta_3}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K + v_h^2 L - \left(2\mu_5^2 + 3v_\eta v_h M\right)\sin(2\alpha)\right),$$

$$M_{A_2}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K' + v_h^2 L' + \left(2\mu_5^2 + v_h v_\eta M\right)\sin(2\alpha)\right),$$

$$M_{A_3}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K' + v_h^2 L' - \left(2\mu_5^2 + v_h v_\eta M\right)\sin(2\alpha)\right),$$

$$M_{\eta_2^+}^2 = \frac{1}{2}\left(2\mu_4^2 + \lambda_3 v_\eta^2 + \lambda_4 v_h^2 + (2\mu_5^2 + 2v_\eta v_h M)\sin(2\alpha)\right),$$

$$M_{\eta_3^+}^2 = \frac{1}{2}\left(2\mu_4^2 + \lambda_3 v_\eta^2 + \lambda_4 v_h^2 - (2\mu_5^2 + 2v_\eta v_h M)\sin(2\alpha)\right).$$

$$K = \lambda_3 + \lambda_5 + 2\lambda_7, \quad K' = \lambda_3 + \lambda_5 - 2\lambda_7,$$
$$L = \lambda_4 + \lambda_6 + 2\lambda_8, \quad L' = \lambda_4 + \lambda_6 - 2\lambda_8,$$
$$M = \lambda_9 + \lambda_{10}, \quad O = \lambda_6 + 2\lambda_8.$$

The Model

Scalar mass spectrum

$$M_h^2 = \frac{2v_h^3\lambda_2 - \mu_3^2 v_\eta}{v_h}\cos(\alpha)^2 + \frac{2v_\eta^3\lambda_1 - \mu_3^2 v_h}{v_\eta}\sin(\alpha)^2 + \left(\mu_3^2 + v_h v_\eta L\right)\sin(2\alpha),$$

$$M_{\eta_1}^2 = \frac{2v_h^3\lambda_2 - \mu_3^2 v_\eta}{v_h}\cos(\alpha)^2 + \frac{2v_\eta^3\lambda_1 - \mu_3^2 v_h}{v_\eta}\sin(\alpha)^2 - \left(\mu_3^2 + v_h v_\eta L\right)\sin(2\alpha),$$

$$M_{A_1}^2 = -\frac{\left(v_h\cos(\alpha) + v_\eta\sin(\alpha)\right)^2\left(\mu_3^2 + 2v_h v_\eta\lambda_8\right)}{v_h v_\eta},$$

$$M_{\eta_1^+}^2 = -\frac{\left(v_h\cos(\alpha) + v_\eta\sin(\alpha)\right)^2\left(\mu_3^2 + 2v_h v_\eta O\right)}{v_h v_\eta},$$

Z_2 odd
(2-IDM)

$$M_{\eta_2}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K + v_h^2 L + \left(2\mu_5^2 + 3v_\eta v_h M\right)\sin(2\alpha)\right),$$

$$M_{\eta_3}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K + v_h^2 L - \left(2\mu_5^2 + 3v_\eta v_h M\right)\sin(2\alpha)\right),$$

$$M_{A_2}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K' + v_h^2 L' + \left(2\mu_5^2 + v_h v_\eta M\right)\sin(2\alpha)\right),$$

$$M_{A_3}^2 = \frac{1}{2}\left(2\mu_4^2 + v_\eta^2 K' + v_h^2 L' - \left(2\mu_5^2 + v_h v_\eta M\right)\sin(2\alpha)\right),$$

$$M_{\eta_2^+}^2 = \frac{1}{2}\left(2\mu_4^2 + \lambda_3 v_\eta^2 + \lambda_4 v_h^2 + (2\mu_5^2 + 2v_\eta v_h M)\sin(2\alpha)\right),$$

$$M_{\eta_3^+}^2 = \frac{1}{2}\left(2\mu_4^2 + \lambda_3 v_\eta^2 + \lambda_4 v_h^2 - (2\mu_5^2 + 2v_\eta v_h M)\sin(2\alpha)\right).$$

$$K = \lambda_3 + \lambda_5 + 2\lambda_7, \quad K' = \lambda_3 + \lambda_5 - 2\lambda_7,$$
$$L = \lambda_4 + \lambda_6 + 2\lambda_8, \quad L' = \lambda_4 + \lambda_6 - 2\lambda_8,$$
$$M = \lambda_9 + \lambda_{10}, \quad O = \lambda_6 + 2\lambda_8.$$

Neutrino Phenomenology

Light LH Majorana neutrinos get masses via Type-I Seesaw:

$$m_\nu = -m_{\mathrm{D}_{3\times 5}} M^{-1}_{\mathrm{R}_{5\times 5}} m^{\mathrm{T}}_{\mathrm{D}_{3\times 5}}$$

Neutrino Phenomenology

Light LH Majorana neutrinos get masses via Type-I Seesaw:

$$m_\nu = -m_{\mathrm{D}_{3\times 5}} M^{-1}_{\mathrm{R}_{5\times 5}} m^{\mathrm{T}}_{\mathrm{D}_{3\times 5}}$$

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

Two-zero textures
[P. H. Frampton, *et al*. '02],
[P. O. Ludl, et al. '11,
D. Meloni et al. '14]

These textures:
Consistent with experimental data.
Allows both mass orderings (NO, IO).

Neutrino Phenomenology

Light LH Majorana neutrinos get masses via Type-I Seesaw:

$$m_\nu = -m_{\mathrm{D}_{3\times 5}} M^{-1}_{\mathrm{R}_{5\times 5}} m^{\mathrm{T}}_{\mathrm{D}_{3\times 5}}$$

Two complex zeros

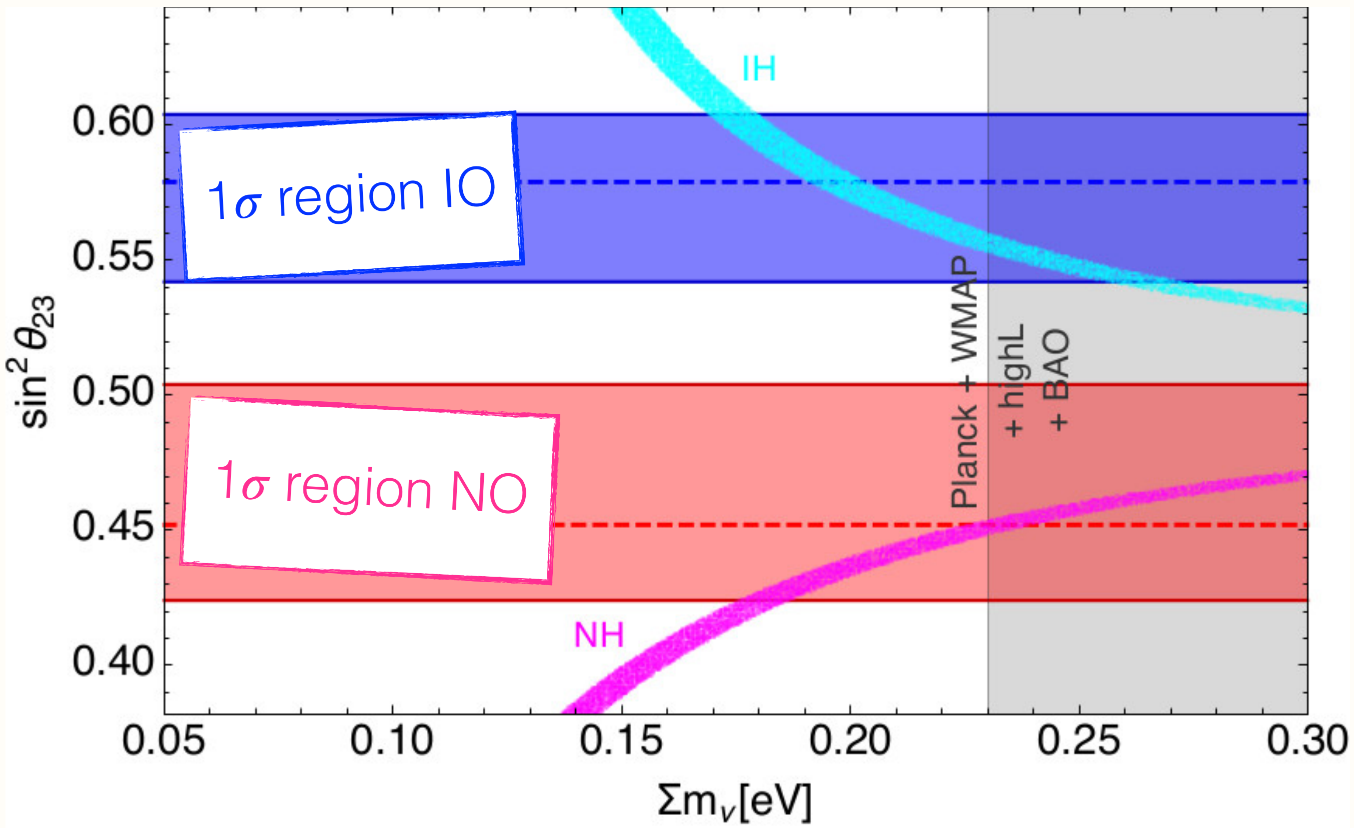
$$m_\nu^{(\mathrm{A})} \equiv \begin{pmatrix} a & 0 & b \\ 0 & 0 & c \\ b & c & d \end{pmatrix}$$

Two-zero textures
[P. H. Frampton, *et al*. '02],
[P. O. Ludl, et al. '11,
D. Meloni et al. '14]

These textures:
Consistent with experimental data.
Allows both mass orderings (NO, IO).

Neutrino Phenomenology

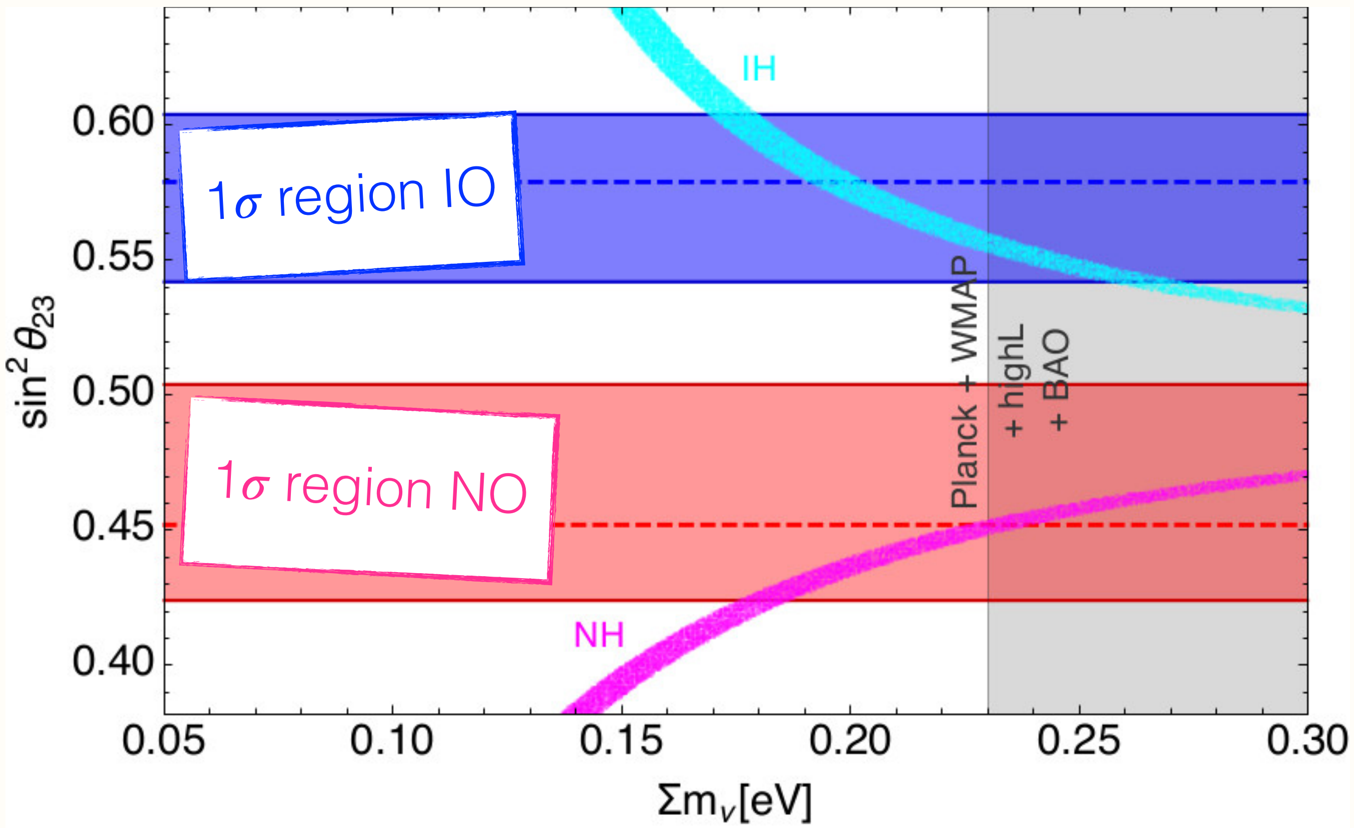
Correlation: Atmospheric mixing angle and sum of light neutrino masses

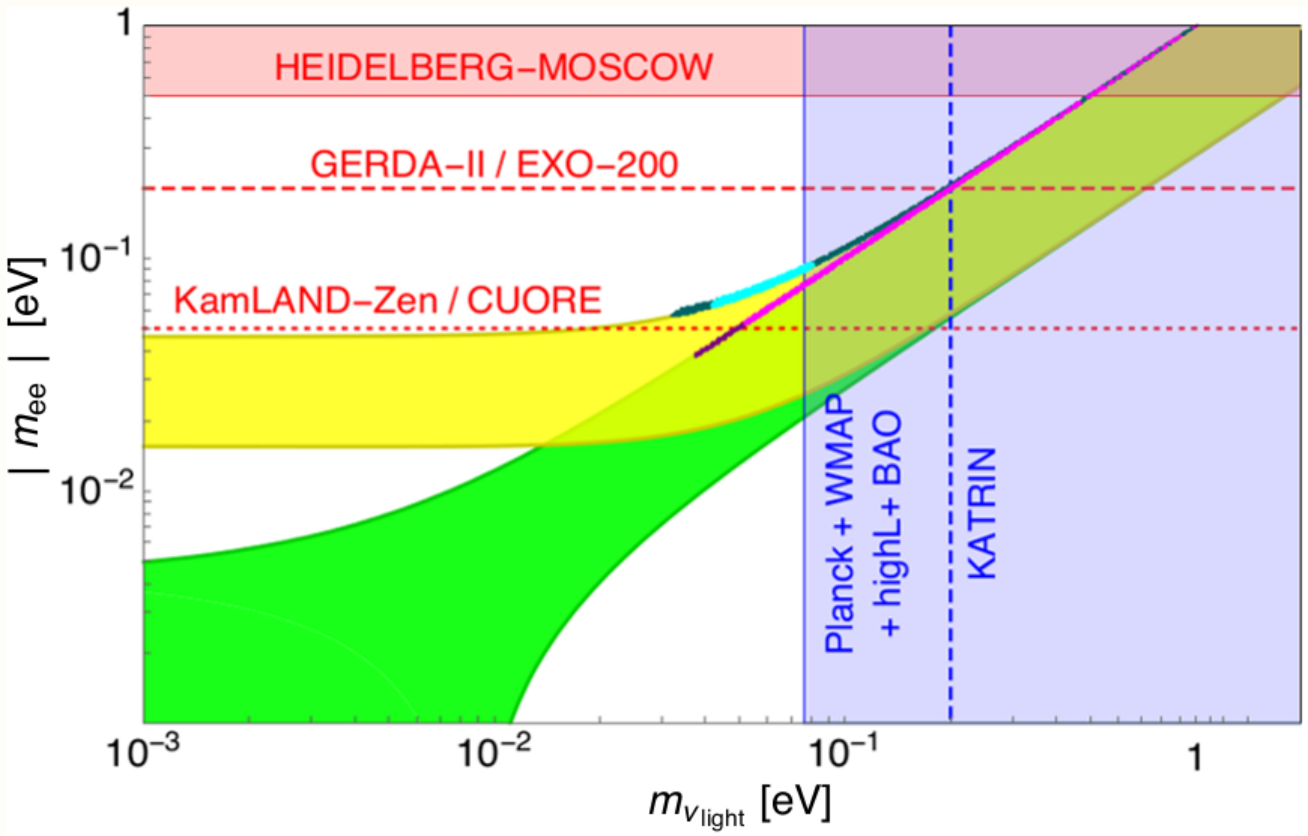


Input data: [Gonzalez-Garcia, *et al.* '15]

Neutrino Phenomenology

Correlation: Atmospheric mixing angle and sum of light neutrino masses



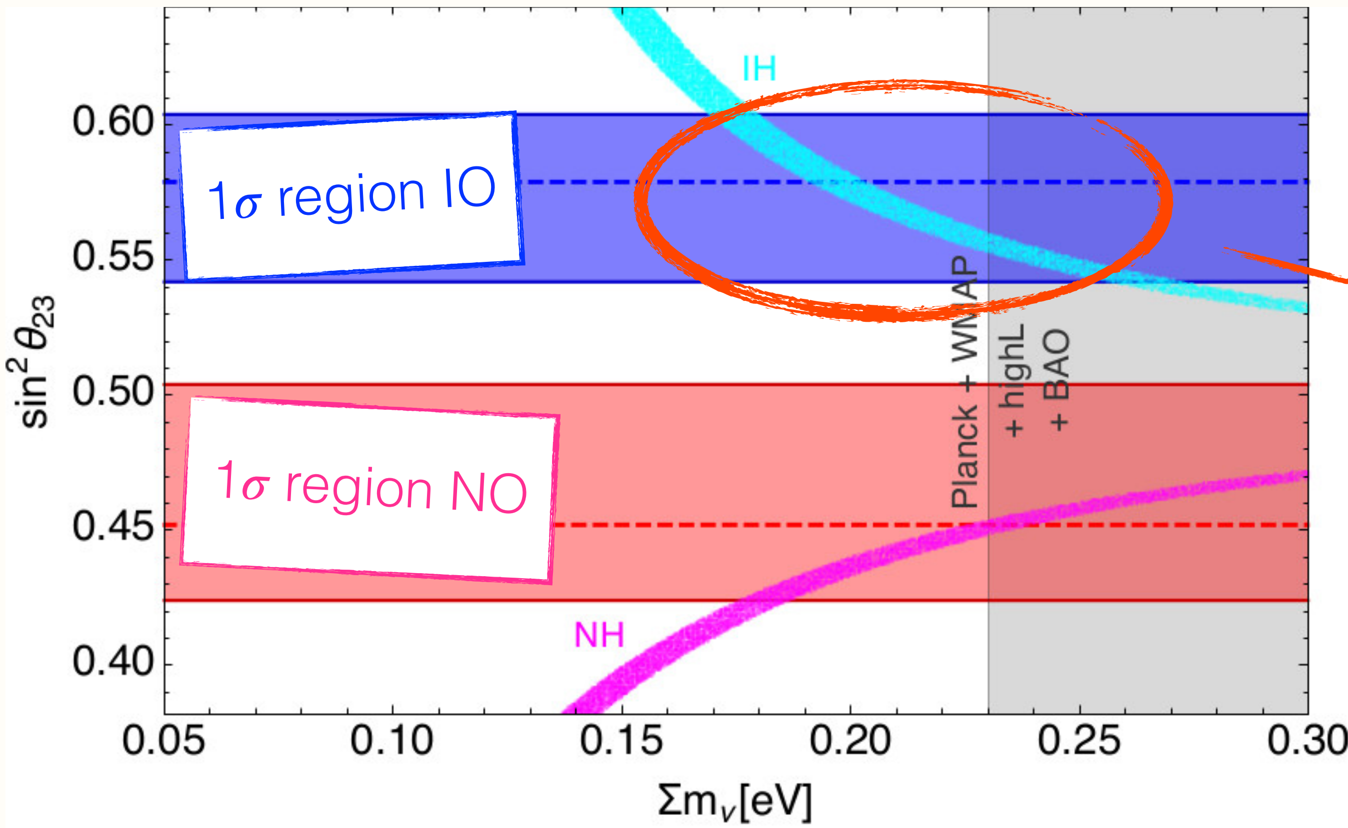


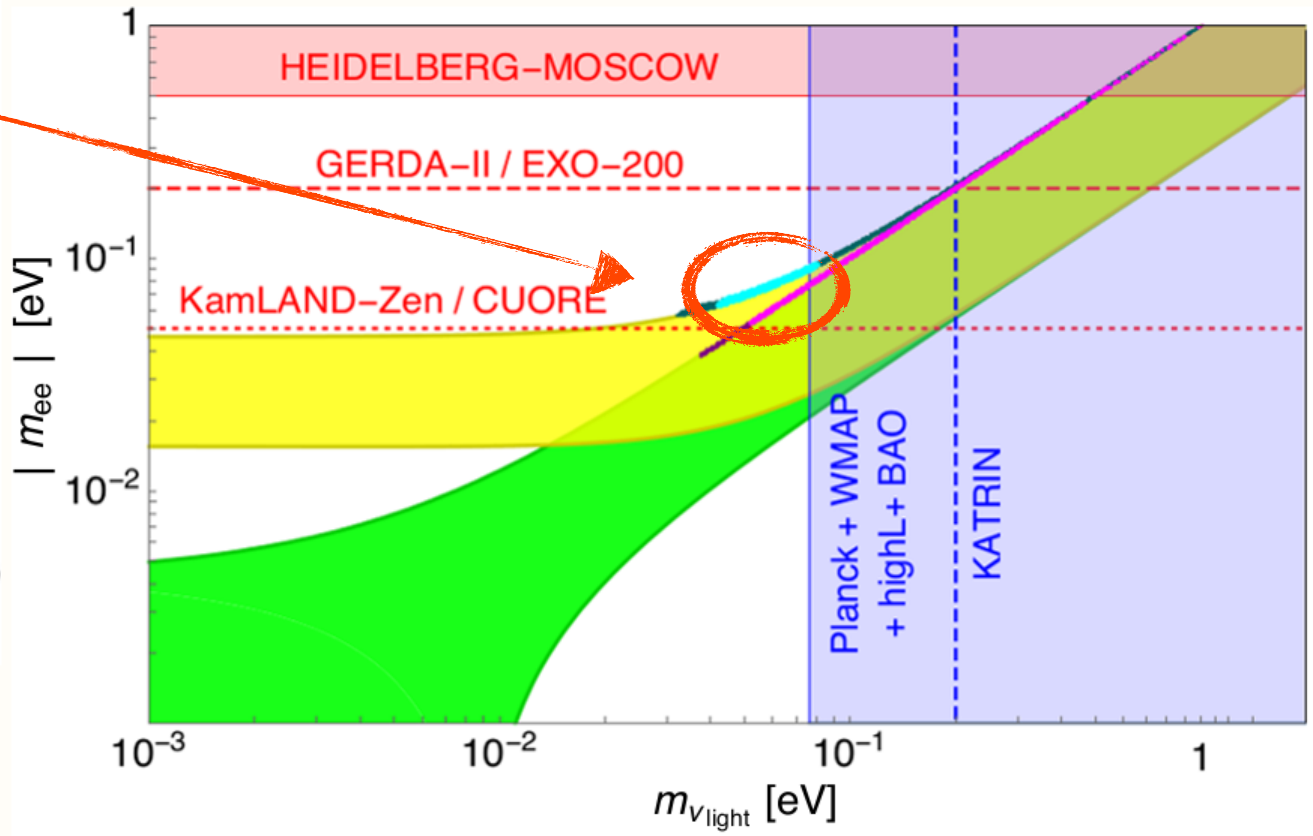
Lower bound for the neutrinoless double beta decay effective mass $|m_{ee}|$

Input data: [Gonzalez-Garcia, *et al.* ’15]

Neutrino Phenomenology

Correlation: Atmospheric mixing angle and sum of light neutrino masses





Lower bound for the neutrinoless double beta decay effective mass $|m_{ee}|$

Input data: [Gonzalez-Garcia, *et al.* '15]

DM Phenomenology

Numerical scan using MicrOMEGAs [G. Belanger, *et al.* '08] over a 13 dim. CP conserving potential (10 real couplings and 3 μ-terms) constraining the parameter region.

Constrains

Vacuum stability:

Potential perturbativity:

Experimental bounds to masses: [A. Pierce et al. '07, E. Lundstrom et al '03]

DM Phenomenology

Numerical scan using MicrOMEGAs [G. Belanger, *et al.* '08] over a 13 dim. CP conserving potential (10 real couplings and 3 μ-terms) constraining the parameter region.

Constrains

Vacuum stability:

$$\lambda_1 > 0, \qquad \lambda_2 > 0, \qquad \begin{aligned} &\lambda_1 + \lambda_2 + 3\left(\lambda_4 + \lambda_6 + \min\{-2\lambda_8,\, 0\}\right) \\ &+ 3\left(\lambda_3 + \lambda_5 + \min\{-2|\lambda_7|,\, 0\}\right) - 6\left(|\lambda_9| + |\lambda_1 0|\right) > 0. \end{aligned}$$

Potential perturbativity:

Experimental bounds to masses: [A. Pierce et al. '07, E. Lundstrom et al '03]

DM Phenomenology

Numerical scan using MicrOMEGAs [G. Belanger, *et al.* '08] over a 13 dim. CP conserving potential (10 real couplings and 3 μ-terms) constraining the parameter region.

Constrains

Vacuum stability:

$$\lambda_1 > 0, \qquad \lambda_2 > 0, \qquad \begin{aligned} &\lambda_1 + \lambda_2 + 3\left(\lambda_4 + \lambda_6 + \min\{-2\lambda_8,\, 0\}\right) \\ &+ 3\left(\lambda_3 + \lambda_5 + \min\{-2|\lambda_7|,\, 0\}\right) - 6\left(|\lambda_9| + |\lambda_1 0|\right) > 0. \end{aligned}$$

Potential perturbativity:

$$\lambda_i < \sqrt{4\pi}, \qquad 0.5 < \tan(\beta) = \frac{v_h}{v_\eta} < 50.$$

Experimental bounds to masses: [A. Pierce et al. '07, E. Lundstrom et al '03]

DM Phenomenology

Numerical scan using MicrOMEGAs [G. Belanger, *et al.* '08] over a 13 dim. CP conserving potential (10 real couplings and 3 μ-terms) constraining the parameter region.

Constrains

Vacuum stability:

$$\lambda_1 > 0, \qquad \lambda_2 > 0, \qquad \begin{aligned} &\lambda_1 + \lambda_2 + 3\left(\lambda_4 + \lambda_6 + \min\{-2\lambda_8, 0\}\right) \\ &+ 3\left(\lambda_3 + \lambda_5 + \min\{-2|\lambda_7|, 0\}\right) - 6\left(|\lambda_9| + |\lambda_1 0|\right) > 0. \end{aligned}$$

Potential perturbativity:

$$\lambda_i < \sqrt{4\pi}, \qquad 0.5 < \tan(\beta) = \frac{v_h}{v_\eta} < 50.$$

Experimental bounds to masses: [A. Pierce et al. '07, E. Lundstrom et al '03]

$$M_{\eta^{\pm}_{2,3}} > 70\mathrm{GeV}, \qquad M_{A_{2,3}} > 110\mathrm{GeV}.$$

DM Phenomenology

Low mass region ($M_{\eta 2} < M_W$)[M. S. Boucenna *et al.* '11]:

$$\eta_2\, \eta_2\, (A_2) \xrightarrow{h,\ \eta_1,\ (A_1,\ Z)} f\ f,$$

Intermediate & high mass region ($M_W \lesssim M_{\eta 2} \lesssim 500$ GeV):

$$\eta_2\, \eta_2\, (A_2) \xrightarrow{h,\ \eta_1,\ A_2,\ \eta_2^+,\ Z,\ *} W^+ W^-,\ Z\, Z.$$

Indirect Detection (gamma ray) Fermilat [M. Ackermann et al.'15], Hess [Hess collab. '11].

Measured relic density, Planck [Planck Collab.'15]

Direct Detection (Spin Independent cross section per nucleon) Lux [Lux collab. '15], Xenon [Xenon1T collab. '12].

DM Phenomenology

Low mass region ($M_{\eta 2} < M_W$)[M. S. Boucenna *et al.* '11]:

$$\eta_2\,\eta_2\,(A_2) \xrightarrow{h,\ \eta_1,\ (A_1,\ Z)} f\,\bar{f},$$

Intermediate & high mass region ($M_W \lesssim M_{\eta 2} \lesssim 500$ GeV):
[Cirelli, *et al. '05]*

$$\eta_2\,\eta_2 \xrightarrow{h,\ \eta_1,\ A_2,\ \eta_2^+,\ Z,\ *} W^+\,W^-,\ Z\,Z.$$

Indirect Detection (gamma ray) Fermilat [M. Ackermann et al.'15], Hess [Hess collab. '11].

Measured relic density, Planck [Planck Collab.'15]

Direct Detection (Spin Independent cross section per nucleon) Lux [Lux collab. '15], Xenon [Xenon1T collab. '12].

DM Phenomenology

Low mass region ($M_{\eta 2} < M_W$)[M. S. Boucenna *et al.* '11]:

$$\eta_2\,\eta_2\,(A_2) \xrightarrow{h,\ \eta_1,\ (A_1,\ Z)} f\,f,$$

Intermediate & high mass region ($M_W \lesssim M_{\eta 2} \lesssim 500$ GeV):
[Cirelli, *et al.* '05]

$$\eta_2\,\eta_2 \xrightarrow{h,\ \eta_1,\ A_2,\ \eta_2^+,\ Z,\ *} W^+\,W^-,\ Z\,Z.$$

Indirect Detection (gamma ray) Fermilat [M. Ackermann et al.'15], Hess [Hess collab, '11].

Measured relic density, Planck [Planck Collab.'15]

Direct Detection (Spin Independent cross section per nucleon) Lux [Lux collab. '15], Xenon [Xenon1T collab. '12].

DM Phenomenology

Low mass region ($M_{\eta_2} < M_W$) [M. S. Boucenna *et al.*'11]:

$$\eta_2\, \eta_2\, (A_2) \xrightarrow{h,\ \eta_1,\ (A_1,\ Z)} f\, f,$$

Intermediate & high mass region ($M_W \lesssim M_{\eta_2} \lesssim 500$ GeV):
[Cirelli, *et al.* '05]

$$\eta_2\, \eta_2 \xrightarrow{h,\ \eta_1,\ A_2,\ \eta_2^+,\ Z,\ *} W^+ W^-,\ Z\, Z.$$

in progress

Indirect Detection (gamma ray) Fermilat [M. Ackermann et al.'15], Hess [Hess collab, '11].

Measured relic density, Planck [Planck Collab.'15]

Direct Detection (Spin Independent cross section per nucleon) Lux [Lux collab. '15], Xenon [Xenon1T collab. '12].

Conclusions

- Interesting Neutrino and DM phenomenology arises from an A_4 flavour symmetric model, broken by a flavon ϕ into a Z_2.
- Three RH neutrinos (Z_2 even) are responsible for giving mass to the light neutrino (via type I seesaw).
- Light neutrino mass and mixing in agreement with the experimental data and both neutrino mass orderings (NO, IO).
- Correlation between θ_{23} and the sum of the lightest neutrino masses is obtained.
- Lower bound for neutrinoless double beta decay effective mass, $|m_{ee}|$.
- DM (relic density) constrains parameter region. But more statistic is needed.

Dziękuję.

/d͡ʑɛŋˈku.jɛ/

(Thank you.)

Backup

Flavour Symmetry Breaking of A_4 into Z_2 by choosing the vev alignments:

$$\left\langle H^0 \right\rangle = v_h \neq 0, \quad \left\langle \eta_1^0 \right\rangle = v_\eta \neq 0, \quad \left\langle \eta_{2,3}^0 \right\rangle = 0, \quad \langle \phi_1 \rangle = v_\phi \neq 0, \quad \langle \phi_{2,3} \rangle = 0.$$

The Majorana neutrino mass matrix:

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

Backup

The Dirac Neutrino mass matrix:

Model A

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

Model B

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

Backup

- Light neutrinos get Majorana masses (type I see-saw), $m_\nu = -m_{\mathrm{D}_{3\times5}} M^{-1}_{\mathrm{R}_{5\times5}} m^{\mathrm{T}}_{\mathrm{D}_{3\times5}}$

Model A

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

where

$$a = \frac{(y_4^\nu v_h)^2}{M_2}, \qquad b = \frac{y_1^\nu y_5^\nu v_\eta v_h}{y_3^N v_\phi} - \frac{y_2^N y_4^\nu y_5^\nu v_h^2}{y_3^N M_2},$$

$$c = \frac{y_2^\nu y_5^\nu v_\eta v_h}{y_3^N v_\phi}, \quad d = \frac{(y_2^N y_5^\nu v_h)^2}{(y_3^N)^2 M_2} - \frac{(y_5^\nu v_h)^2 M_1}{(y_3^N v_\phi)^2} + 2\, \frac{y_3^\nu y_5^\nu v_\eta v_h}{y_3^N v_\phi}.$$

Backup

- Model B

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

where

$$a = \frac{(y_4^\nu v_h)^2}{M_2}, \qquad b = \frac{y_1^\nu y_5^\nu v_\eta v_h}{y_3^N v_\phi} - \frac{y_2^N y_4^\nu y_5^\nu v_h^2}{y_3^N M_2},$$

$$c = \frac{y_3^\nu y_5^\nu v_\eta v_h}{y_3^N v_\phi}, \quad d = \frac{(y_2^N y_5^\nu v_h)^2}{(y_3^N)^2 M_2} - \frac{(y_5^\nu v_h)^2 M_1}{(y_3^N v_\phi)^2} + 2\,\frac{y_2^\nu y_5^\nu v_\eta v_h}{y_3^N v_\phi}.$$

- These mass matrices has the two zero textures: B_3 for model A and B_4 for model B.

Backup

Model B (Two zero texture B_4)