S3 multi-Higgs models: DM and leptogenesis

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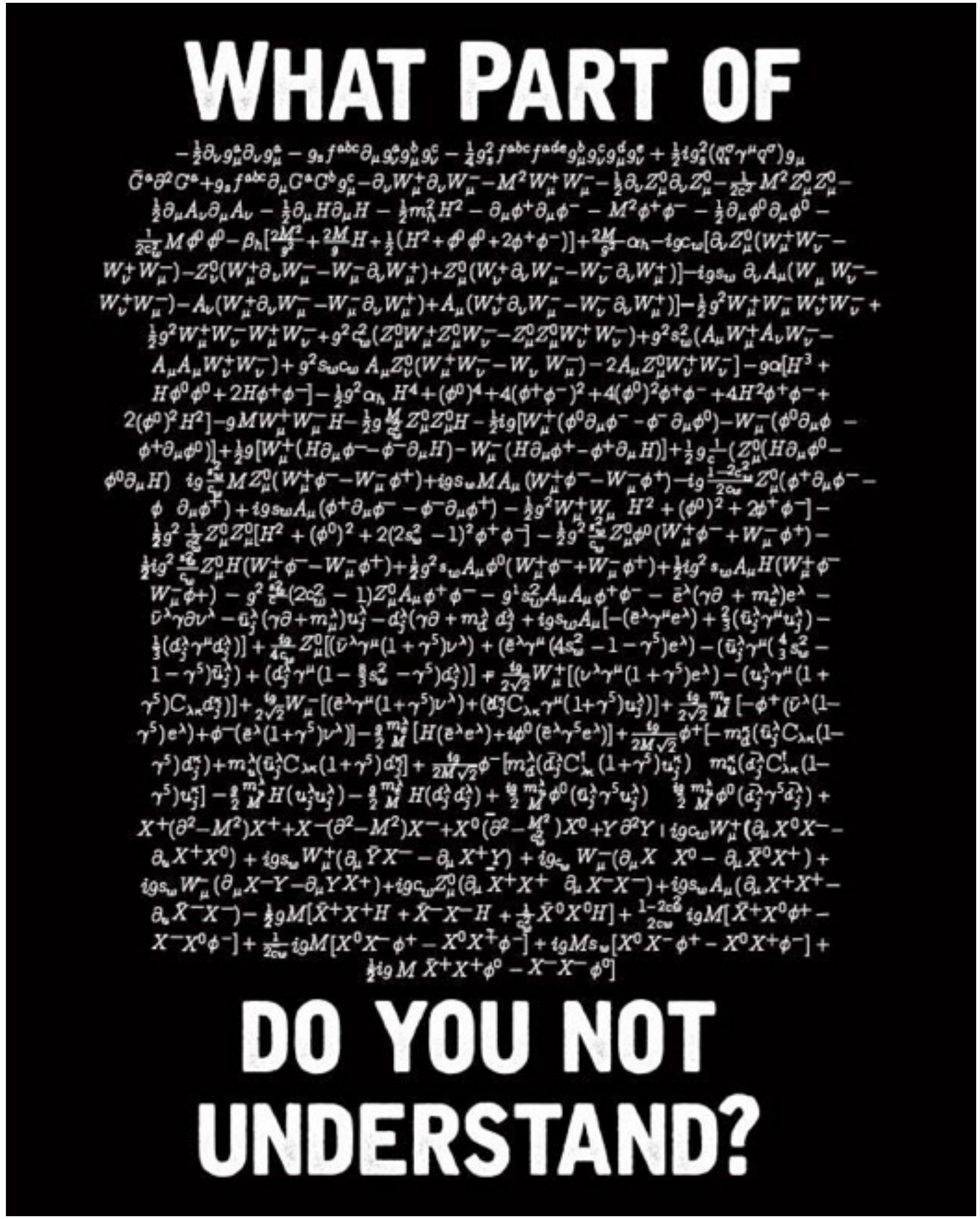
Outline

- Our strategy
- S3 models with extended Higgs sector
- Quarks and leptons
- DM in S3-4H
- Leptogenesis in S3-3H
- Conclusions


STANDARD MODEL
LAGRANGIAN


WHAT PART OF
DO YOU NOT UNDERSTAND?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DO YOU NOT UNDERSTAND?

How to go BSM?

- Many ways to go BSM
- Usually: add symmetries, add particles, add interactions
- All of the above
- Messy…
- I will concentrate on masses and mixings

Some aspects of the flavour problem

- Quark and charged lepton masses very different, very hierarchical

$$m_u : m_c : m_t \sim 10^{-6} : 10^{-3} : 1$$

$$m_d : m_s : m_b \sim 10^{-4} : 10^{-2} : 1$$

$$m_e : m_\mu : m_\tau \sim 10^{-5} : 10^{-2} : 1$$

- Neutrino masses unknown, only difference of squared masses.
- Type of hierarchy (normal or inverted) also unknown

- Quark mixing angles

$$\theta_{12} \approx 13.0^o$$
$$\theta_{23} \approx 2.4^o$$
$$\theta_{13} \approx 0.2^o$$

- Neutrino mixing angles

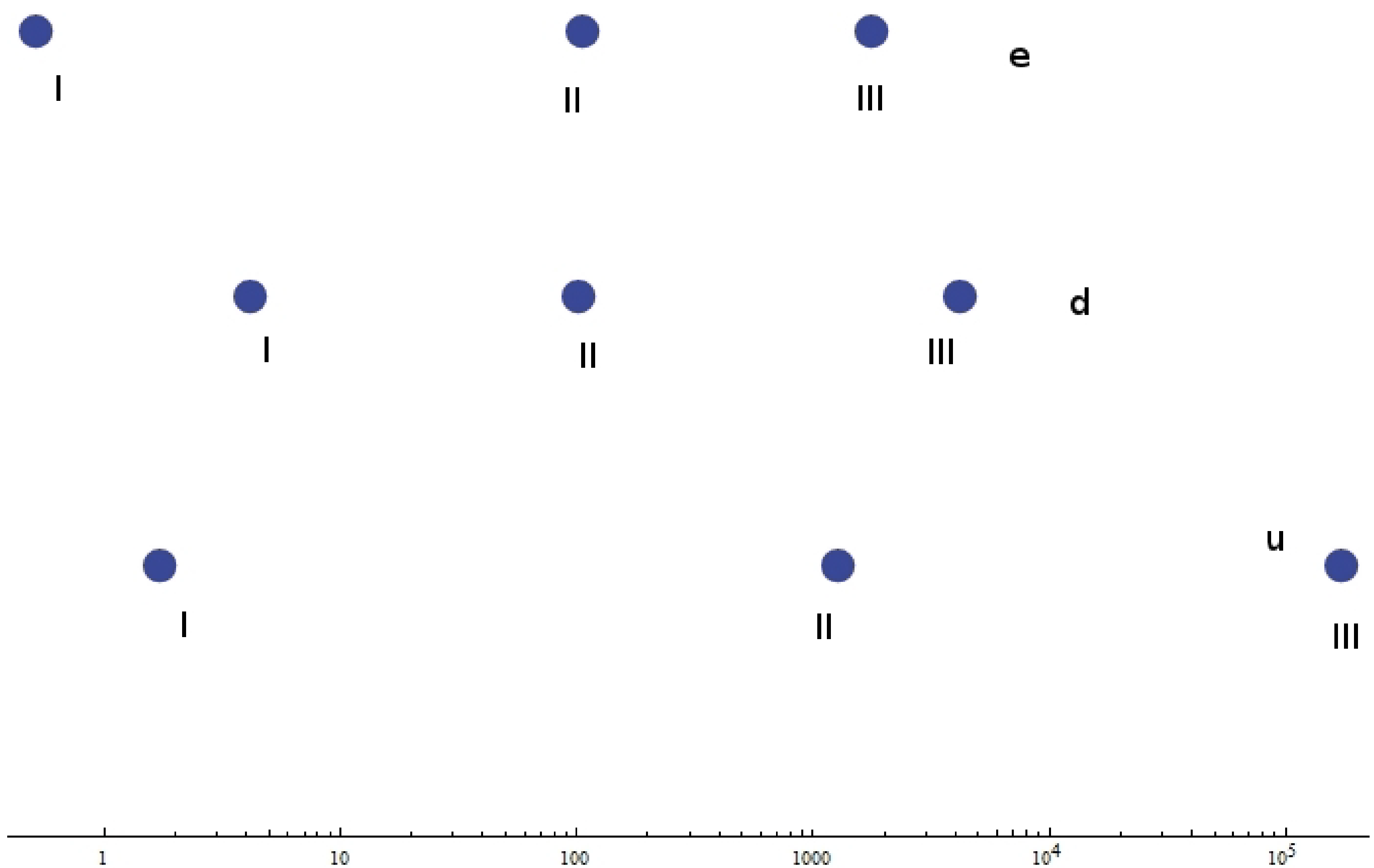
$$\Theta_{12} \approx 34.0^o$$
$$\Theta_{23} \approx 45^o$$
$$\Theta_{13} \approx 8.5^o$$

- Small mixing in quarks, large mixing in neutrinos. Very different

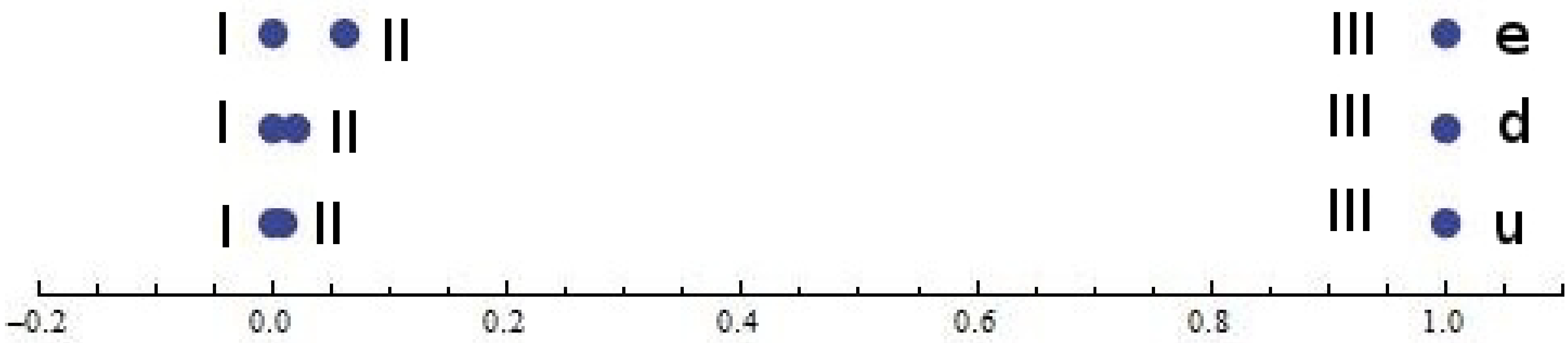
- Is there an underlying symmetry?

How do we choose a flavour symmetry?

- Several ways:
- Look for inspiration in a high energy extension of SM, i.e. strings or GUTs (see S. King talk)
- Look at low energy phenomenology
- At some point they should intersect…
- In here:
  - Find the smallest flavour symmetry suggested by data
  - Explore how generally it can be applied (universally)
  - Follow it to the end
  - Compare it with the data (Neruda's quote…)



Logarithmic plot of masses



Plot of mass ratios

Suggests a 2⊕1 structure

Flavour/family symmetries more symmetries

- Add the flavour symmetry of your choice
- Continuous → upon breaking might generate massless Goldstone bosons U(1), SU(3)...

- Discrete Z_N, A4, S3, S4, Q6, Δ27...
  → might also generate accidental continuous symmetries
- Explain masses and mixings of quarks and leptons
- Usually also add more particles → Higgs

Multi-Higgs models more particles

- 2HDM without SUSY
  - widely studied
  - different versions depending on how they couple to the other SM particles
- 3 or more HDM also possible
- Extra singlet Higgs models NMSSM
- Complex MSSM ℂMSSM
- FCNC's
- More sources of CP violation
- Candidates for dark matter, with some discrete symmetry
- Might give explanation for the mass hierarchies and mixing of quarks and leptons
- More scalar particles give ways to test them

N-Higgs doublet models — NHDM

- Add more complex electroweak doublets
  All with same hyper charge Y=1

$$V(\phi) = Y_{ij}\phi_i^\dagger\phi_j + Z_{ijkl}(\phi_i^\dagger\phi_j)(\phi_k^\dagger\phi_l)\,.$$

- $N^2 + N^2(N^2+1)/2$ real parameters:
  12 for 2HDM, 54 for 3HDM…
- Potential must be bounded by below, no charge or colour breaking minima
- Must respect unitarity bounds
- Can have CP breaking minima $\rightarrow$ baryogenesis (or disaster)

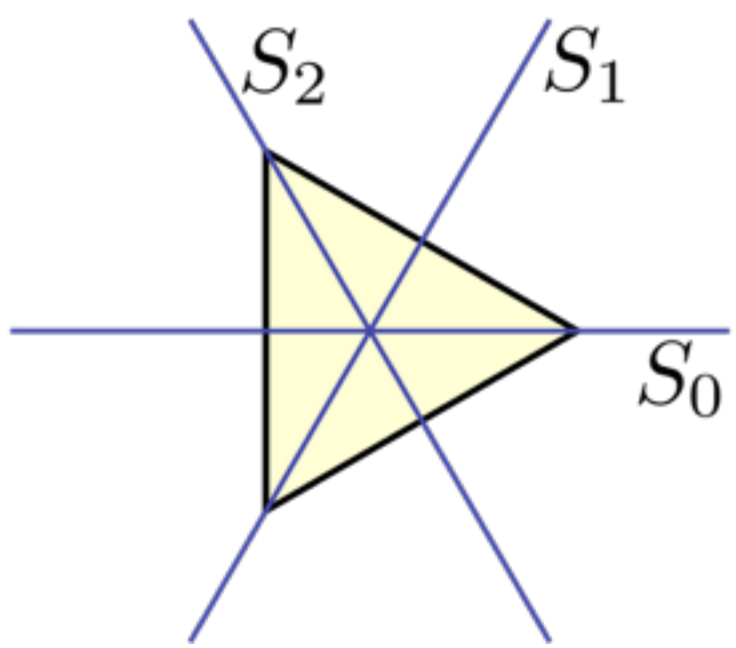
3HDM

- Even more Higgses $\Longrightarrow$ 54 real parameters in potential
- Complemented with additional symmetry(ies)
- Studies started in the 70's, hope to find global symmetry that explains the mass and mixing patterns
- The first symmetries to be added were the permutational groups S3 and S4
- Another approach was to use Δ(54) or Δ(27) hierarchy in masses come from vevs. Did not generate a hierarchical vev structure v3>>v2>>v1
- Different modern versions of these models exist

e.g.,I.de Medeiros, D. Emmanuel-Costa (2011) for Δ(54) ,

3HDM with S3

- Low-energy model
- Extend the concept of flavour to the Higgs sector by adding two more eW doublets



- Add symmetry: permutation symmetry of three objects, symmetry operations (reflections and rotations) that leave an equilateral triangle invariant
- 3HDM with symmetry S3:
  8 couplings in the Higgs potential

A sample of S3 models

S. Pakvasa et al, Phys. Lett. 73B, 61 (1978)

E. Derman, Phys. Rev. D19, 317 (1979)

D. Wyler, Phys. Rev. D19, 330 (1979)

R. Yahalom, Phys. Rev. D29, 536 (1984)

A. Mondragon et al, Phys. Rev. D59, 093009, (1999)

J. Kubo, A. Mondragon, et al, Prog. Theor. Phys. 109, 795 (2003)

J. Kubo et al, Phys. Rev. D70, 036007 (2004)

S. Chen, M. Frigerio and E. Ma, Phys. Rev. D70, 073008 (2004)

A. Mondragon et al, Phys. Rev. D76, 076003, (2007)

S. Kaneko et al, hep-ph/0703250, (2007)

D. Meloni et al, Nucl. Part. Phys. 38 015003, (2011)

T. Teshima et al, Phys.Rev. D84 (2011) 016003 Phys.Rev. D85 105013 (2012)

F. Gonzalez Canales, A&M. Mondragon Fort. der Physik 61, Issue 4-5 (2013)

H.B. Benaoum, Phys. RevD.87.073010 (2013)

E. Ma and B. Melic, arXiv:1303.6928

F. Gonzalez Canales, A. &M Mondragon, U. Salda~na, L. Velasco, arXiv:1304.6644

R. Jora et al, Int.J.Mod.Phys. A28 (2013),1350028

A. E. Cárcamo Hernández, E. Cataño Mur, R. Martinez, Phys.Rev. D90 (2014) no.7, 073001

A.E. Cárcamo, I. de Medeiros E. Schumacheet, Phys.Rev. D93 (2016) no.1, 016003

S. Pakvasa and H. Sugawara, Phys. Lett. 73B, 61 (1978)

E. Derman, Phys. Rev. D19, 317 (1979)

D. Wyler, Phys. Rev. D19, 330 (1979)

R. Yahalom, Phys. Rev. D29, 536 (1984)

Y. Koide, Phys. Rev. D60, 077301 (1999)

J. Kubo et al, Phys. Rev. D70, 036007 (2004)

S. Chen et al, Phys. Rev. D70, 073008 (2004)

O. Felix-Beltran, M.M., et al, J.Phys.Conf.Ser. 171, 012028 (2009)

D. Meloni et al, Nucl. Part. Phys. 38 015003, (2011)

G. Bhattacharyya et al, Phys. Rev. D83, 011701 (2011)

D. Meloni, JHEP 1205 (2012) 124

S. Dev et al, Phys.Lett. B708 (2012) 284-289

S. Zhou, Phys.Lett. B704 (2011) 291-295

E. Barradas et al, 2014

P. Das et al, 2014

Just a sample, there are many more…
I apologise for those not included

- Smallest non-Abelian discrete group
- Has irreducible representations, 2, 1_S and 1_A
- We add three right-handed neutrinos to implement the see-saw mechanism
- We apply the symmetry "universally" to quarks, leptons and Higgs-es
  - First two families in the doublet
  - Third family in symmetric singlet
- Three sectors related, we treat them simultaneously

Predictions, advantages?

- Possible to reparametrize mixing matrices in terms of mass ratios, successfully
- Reproduces well CKM → one less parameter as SM
- PMNS → fix one mixing angle, predictions for the other two within experimental range
- Predicts reactor mixing angle $\theta 13 \neq 0$
- No extra flavons
- FCNCs suppressed by symmetry
- Higgs potential has 8 couplings
- Underlying symmetry in quark, leptons and Higgs → residual symmetry of a more fundamental one?
- Lots of Higgses:
  3 neutral, 4 charged,
  2 pseudoscalars
  Natural decoupling limit
- Further predictions will come from Higgs sector:
  decays, branching ratios

A. Mondragón, M. M., F. González, E. Peinado, U. Saldaña, O. Félix, E. Rodríguez, A. Pérez, H. Reyes...; Teshima et al

Quarks

3HDM: $G_{SM} \otimes S_3$

	ψ_L^f	ψ_R^f	Mass matrix	Possible mass textures	
A	$\mathbf{2}$, $1_{\mathbf{S}}$	$\mathbf{2}$, $1_{\mathbf{S}}$	$\begin{pmatrix} \mu_1^f + \mu_2^f & \mu_4^f & \mu_6^f \\ \mu_4^f & \mu_1^f - \mu_2^f & \mu_7^f \\ \mu_8^f & \mu_9^f & \mu_3^f \end{pmatrix}$	$\begin{pmatrix} 0 & \mu_2^f sc\,(3-t^2) & 0 \\ \mu_2^f sc\,(3-t^2) & -2\mu_2^f c^2\,(1-3t^2) & \mu_7^f/c \\ 0 & \mu_7^{f*}/c & \mu_3^f - \mu_1^f - \mu_2^f c^2(1-3t^2) \end{pmatrix}$	
$A^{'}$				$\begin{pmatrix} 0 & \frac{2}{\sqrt{3}}\mu_2^f & 0 \\ \frac{2}{\sqrt{3}}\mu_2^f & 0 & \frac{2}{\sqrt{3}}\mu_7^f \\ 0 & \frac{2}{\sqrt{3}}\mu_9^f & \mu_3^f - \mu_1^f \end{pmatrix}$	NNI
B	$\mathbf{2}$, $1_{\mathbf{A}}$	$\mathbf{2}$, $1_{\mathbf{A}}$	$\begin{pmatrix} \mu_1^f + \mu_2^f & \mu_4^f & \mu_7^f \\ \mu_4^f & \mu_1^f - \mu_2^f & -\mu_6^f \\ -\mu_9^f & \mu_8^f & \mu_3^f \end{pmatrix}$	$\begin{pmatrix} 0 & -\mu_4^f c^2\,(1-3t^2) & 0 \\ -\mu_4^f c^2\,(1-3t^2) & 2\mu_4^f sc\,(3-t^2) & -\mu_6^f/c \\ 0 & -\mu_6^{f*}/c & \mu_3^f - \mu_1^f + \vert\mu_4^f sc(3-t^2) \end{pmatrix}$	
$B^{'}$				$\begin{pmatrix} 0 & -2\mu_4^f & 0 \\ -2\mu_4^f & 0 & -2\mu_6^f \\ 0 & 2\mu_8^f & \mu_3^f - \mu_1^f \end{pmatrix}$	NNI

Table 2: Mass matrices in S_3 family models with three Higgs $SU(2)_L$ doublets: H_1 and H_2, which occupy the S_3 irreducible representation $\mathbf{2}$, and H_S, which transforms as $1_{\mathbf{S}}$ for the cases when both the left- and right-handed fermion fields are in the same assignment. The mass matrices shown here follow a normal ordering of their mass eigenvalues (m_1^f, m_2^f, m_3^f). We have denoted $s = \sin\theta$, $c = \cos\theta$ and $t = \tan\theta$. The third column of this table corresponds to the general case, while the fourth column to a case where we have rotated the matrix to a basis where the elements $(1,1)$, $(1,3)$ and $(3,1)$ vanish. The primed cases, A' or B', are particular cases of the unprimed ones, A or B, with $\theta = \pi/6$ or $\theta = \pi/3$, respectively.

Mass matrices reproduce the NNI or the Fritzsch forms

F. González et al, Phys.Rev. D88 (2013) 096004

Leptons - S3xZ2

- Charged leptons can be also parameterised successfully, no extra free parameters

- Neutrinos: Fixing one mixing angle we obtain the other two

- Neutrinos: S3 predicts $\theta_{13} \neq 0$

  M_1 and M_2 equal → θ_{13} too small

  M_1 and M_2 different → θ_{13} in experimental range

Higgs-es
this is where the model can be tested

General potential

$$
\begin{aligned}
V \;=\; & \mu_1^2\left(H_1^\dagger H_1+H_2^\dagger H_2\right)+\mu_0^2\left(H_s^\dagger H_s\right)+a\left(H_s^\dagger H_s\right)^2+b\left(H_s^\dagger H_s\right)\left(H_1^\dagger H_1+H_2^\dagger H_2\right)\\
&+c\left(H_1^\dagger H_1+H_2^\dagger H_2\right)^2+d\left(H_1^\dagger H_2-H_2^\dagger H_1\right)^2+ef_{ijk}\left(\left(H_s^\dagger H_i\right)\left(H_j^\dagger H_k\right)+h.c.\right)\\
&+f\left\{\left(H_s^\dagger H_1\right)\left(H_1^\dagger H_s\right)+\left(H_s^\dagger H_2\right)\left(H_2^\dagger H_s\right)\right\}+g\left\{\left(H_1^\dagger H_1-H_2^\dagger H_2\right)^2+\left(H_1^\dagger H_2+H_2^\dagger H_1\right)^2\right\}\\
&+h\left\{\left(H_s^\dagger H_1\right)\left(H_s^\dagger H_1\right)+\left(H_s^\dagger H_2\right)\left(H_s^\dagger H_2\right)+\left(H_1^\dagger H_s\right)\left(H_1^\dagger H_s\right)+\left(H_2^\dagger H_s\right)\left(H_2^\dagger H_s\right)\right\} \qquad (1)
\end{aligned}
$$

Felix-Beltrán, Rodríguez-Jáuregui, M.M (2006), Das (2010), Félix-Beltrán

- The minimum of potential can be parameterised in spherical coordinates, two angles and v
- Minimisation fixes one angle to v1/v2 = π/6
  consistent with NNI form of mass matrices
- Has natural decoupling limit
- Predictions for decays and branching rations   work in progress

4HDM -S3 with DM

- We add another doublet, inert, to have a DM candidate. We assign it to the 1A, and thus "saturate" the irreps
- A lot of Higgses (13), but the good features of 3H-S3 remain
- S3 symmetry constrains strongly the allowed couplings

4H-S3 potential

- Most general Lagrangian with 4 Higgs doublets and S3 symmetry, plus Z2 symmetry
- First two generations in a flavour doublet, third in a singlet, extra anti-symmetric singlet is inert → DM candidates

$$
\begin{aligned}
-\mathcal{L}_{Y_f} = & Y_1^f(\bar{\psi}^f_{S,L}\psi^f_{S,R}H_s) + \frac{1}{\sqrt{2}}Y_2^f(\bar{\psi}^f_{1,L}\psi^f_{1,R} + \bar{\psi}^f_{2,L}\psi^f_{2,R})H_s \\
& + \frac{1}{2}Y_3^f[(\bar{\psi}^f_{1,L}H_2 + \bar{\psi}_{2,L}H_1)\psi^f_{1,R} + (\bar{\psi}_{1,L}H_1 - \bar{\psi}^f_{2,L}H_2)\psi^f_{2,R}] \\
& \cancel{+ \frac{1}{\sqrt{2}}Y_4^f(\bar{\psi}^f_{1,L}\psi_{2,R} - \bar{\psi}^f_{2,L}\psi^f_{1,R})H_a} \\
& + \frac{1}{\sqrt{2}}Y_5^f(\bar{\psi}^f_{1,L}H_1 + \bar{\psi}^f_{1,L}H_1 + \bar{\psi}^f_{2,L}H_2)\psi^f_{S,R} \\
& + \frac{1}{\sqrt{2}}Y_6^f(\bar{\psi}^f_{S,L}(H_1\psi^f_{1,R} + H_2\psi^f_{2,R})] + \text{h.c.} \\
& f = d, e.
\end{aligned}
$$

Higgs potential 4H-S3

- We need to find the minima of the potential S3xZ2, which satisfy the stability and unitarity conditions

$$
\begin{aligned}
V_4 = {} & \mu_0^2 H_s^\dagger H_s + \mu_1^2 (H_1^\dagger H_1 + H_2^\dagger H_2) + \mu_2^2 H_a^\dagger H_a \\
& + \lambda_1 (H_1^\dagger H_1 + H_2^\dagger H_2)^2 + \lambda_2 (H_1^\dagger H_2 - H_2^\dagger H_1)^2 \\
& + \lambda_3 [(H_1^\dagger H_1 - H_2^\dagger H_2)^2 + (H_1^\dagger H_2 + H_2^\dagger H_1)^2] \\
& + \lambda_4 [(H_s^\dagger H_1)(H_1^\dagger H_2 + H_2^\dagger H_1) + (H_s^\dagger H_2)(H_1^\dagger H_1 - H_2^\dagger H_2) + \text{h.c.}] \\
& + \lambda_5 (H_s^\dagger H_s)(H_1^\dagger H_1 + H_2^\dagger H_2) \\
& + \lambda_6 [(H_s^\dagger H_1)(H_1^\dagger H_s) + (H_s^\dagger H_2)(H_2^\dagger H_s)] \\
& + \lambda_7 [(H_s^\dagger H_1)(H_s^\dagger H_1) + (H_s^\dagger H_2)(H_s^\dagger H_2) + \text{h.c.}] \\
& + \lambda_8 (H_s^\dagger H_s)^2 \\
& \cancel{+ \lambda_9 [(H_a^\dagger H_2)(H_1^\dagger H_2 + H_2^\dagger H_1) - (H_a^\dagger H_1)(H_1^\dagger H_1 - H_2^\dagger H_2) + h.c.]} \\
& + \lambda_{10} (H_a^\dagger H_a)(H_1^\dagger H_1 + H_2^\dagger H_2) \\
& + \lambda_{11} [(H_a^\dagger H_1)(H_1^\dagger H_a) + (H_a^\dagger H_2)(H_2^\dagger H_a)] \\
& + \lambda_{12} [(H_a^\dagger H_1)(H_a^\dagger H_1) + (H_a^\dagger H_2)(H_a^\dagger H_2) + \text{h.c.}] \\
& \cancel{+ \lambda_{13} (H_a^\dagger H_a)^2 + \lambda_{14} (H_s^\dagger H_a H_a^\dagger H_s) + \lambda_{15} [(H_1^\dagger H_s)(H_2^\dagger H_a) + \text{h.c.}].}
\end{aligned}
$$

4H-S3 potential

- We have to analyse the Higgs potential to find the proper minima:
  - Stability conditions - potential bounded from below
  - Scalar S-matrix is unitary
  - Quartic Higgs couplings are perturbative
- These conditions restrict the allowed parameter space, i.e. couplings
- **Check masses of DM candidates**
- **Calculate relic density**

Stability conditions

$$\lambda_8 > 0$$
$$\lambda_1 + \lambda_3 > 0$$
$$\lambda_5 > -2\sqrt{(\lambda_1+\lambda_3)\lambda_8}$$
$$\lambda_5 + \lambda_6 - 2|\lambda_7| > \sqrt{(\lambda_1+\lambda_3)\lambda_8}$$
$$\lambda_1 - \lambda_2 > 0$$
$$\lambda_1 + \lambda_3 + \mid 2\lambda_4 \mid + \lambda_5 + 2\lambda_7 + \lambda_8 > 0$$
$$\lambda_{13} > 0$$
$$\lambda_{10} > -2\sqrt{(\lambda_1+\lambda_3)\lambda_{13}}$$
$$\lambda_{10} + \lambda_{11} - 2|\lambda_{12}| > \sqrt{(\lambda_1+\lambda_3)\lambda_{13}}$$
$$\lambda_{14} > -2\sqrt{\lambda_8\lambda_{13}}.$$

Unitarity conditions

$$\begin{aligned}
a_1^{\pm} &= (\lambda_1 - \lambda_2 + \frac{\lambda_5+\lambda_6}{2}) \\
&\pm \sqrt{(\lambda_1 - \lambda_2 + \frac{\lambda_5+\lambda_6}{2})^2 - 4[(\lambda_1-\lambda_2)(\frac{\lambda_5+\lambda_6}{2}) - \lambda_4^2]} \\
a_2^{\pm} &= (\lambda_1 + \lambda_2 + 2\lambda_3 + \lambda_8) \\
&\pm \sqrt{(\lambda_1 + \lambda_2 + 2\lambda_3 + \lambda_8)^2 - 4[\lambda_8(\lambda_1+\lambda_2+2\lambda_3) - 2\lambda_7^2]} \\
a_3^{\pm} &= (\lambda_1 - \lambda_2 + 2\lambda_3 + \lambda_8) \\
&\pm \sqrt{(\lambda_1 - \lambda_2 + 2\lambda_3 + \lambda_8)^2 - 4[\lambda_8(\lambda_1+\lambda_2+2\lambda_3) - \frac{\lambda_6^2}{2}]} \\
a_4^{\pm} &= (\lambda_1 + \lambda_2 + \frac{\lambda_5}{2} + \lambda_7) \\
&\pm \sqrt{(\lambda_1 + \lambda_2 + \frac{\lambda_5}{2} + \lambda_7)^2 - 4[(\lambda_1-\lambda_2)(\frac{\lambda_5}{2} + \lambda_7) - \lambda_4^2]}
\end{aligned} \tag{6.132}$$

$$\begin{aligned}
a_5^{\pm} &= (5\lambda_1 - \lambda_2 + 2\lambda_3 + 3\lambda_8) \\
&\pm \sqrt{(5\lambda_1 - \lambda_2 + 2\lambda_3 + 3\lambda_8)^2 - 4[3\lambda_8(5\lambda_1 - \lambda_2 + 2\lambda_3) - \frac{1}{2}(2\lambda_5+\lambda_6)^2]} \\
a_6^{\pm} &= (\lambda_1 + \lambda_2 + 4\lambda_3 + \frac{\lambda_5}{2} + \lambda_6 + 3\lambda_7) \pm ((\lambda_1 + \lambda_2 + 4\lambda_3 + \frac{\lambda_5}{2} + \lambda_6 + 3\lambda_7)^2 - \\
&4[(\lambda_1+\lambda_2+4\lambda_3)(\frac{\lambda_5}{2} + \lambda_6 + 3\lambda_7) - 9\lambda_4^2])^{1/2}
\end{aligned}$$

These are for 3H
4H ones similar

$$\begin{aligned}
b_1 &= \lambda_5 + 2\lambda_6 - \lambda_7 \\
b_2 &= \lambda_5 - 2\lambda_7 \\
b_3 &= 2(\lambda_1 - 5\lambda_1 - 2\lambda_3) \\
b_4 &= 2(\lambda_1 - \lambda_1 - 2\lambda_3) \\
b_5 &= 2(\lambda_1 + \lambda_1 - 2\lambda_3) \\
b_6 &= \lambda_5 - \lambda_6.
\end{aligned} \tag{6.133}$$

Masses

- After electroweak symmetry breaking (Higgs mechanism) we are left with

  13 massive particles!

- One has to be the SM Higgs boson - two candidates
- Another three can be DM particles
- Check SM Higgs boson first

The masses are found by diagonalizing the matrix:

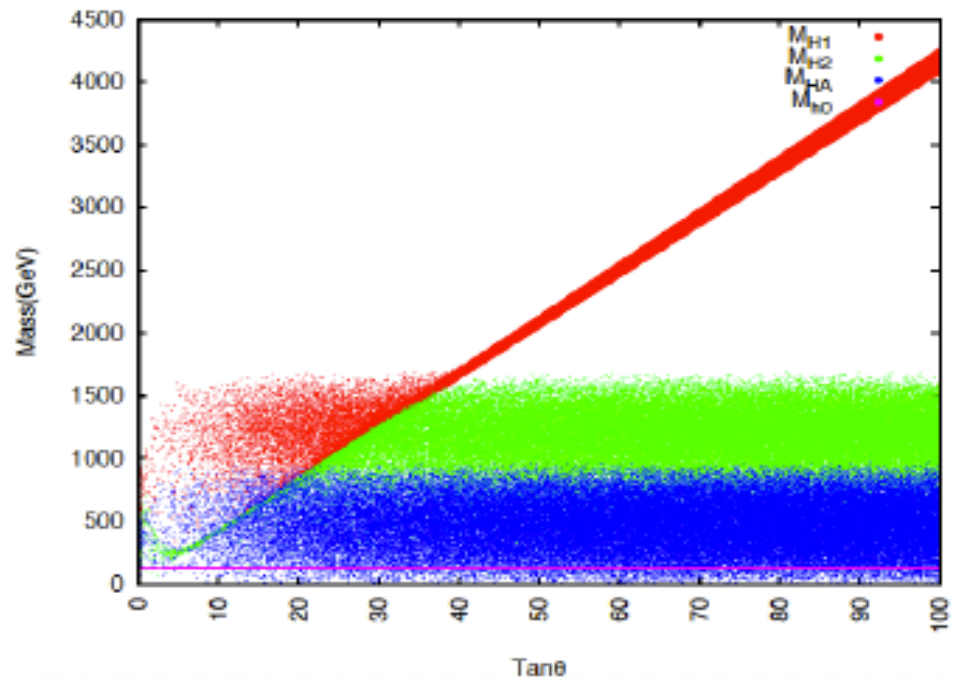
$$(\mathcal{M}_H^2)_{ij} = \frac{1}{2}\frac{\partial^2 V}{\partial H_i \partial H_j}\ |_{min}\ .$$

Which is block diagonal, and all the submatrices have the following form:

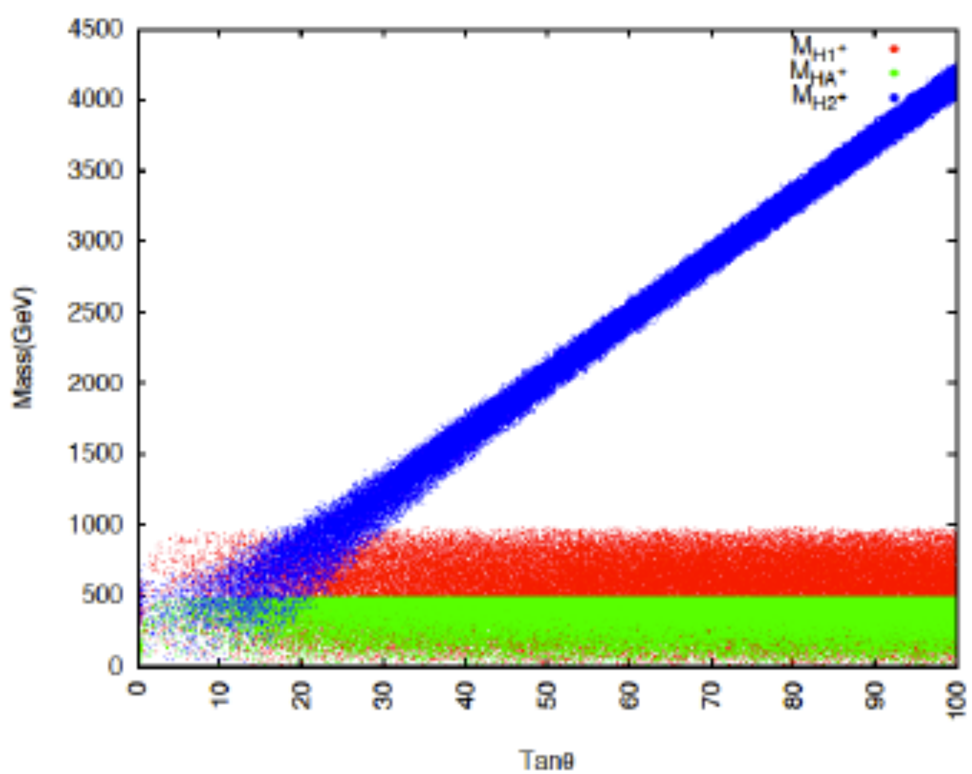
$$m^2_{H^S} = \begin{pmatrix} m_{h_s^n h_s^n} & m_{h_1^n h_s^n} & m_{h_2^n h_s^n} & 0 \\ m_{h_s^n h_1^n} & m_{h_1^n h_1^n} & m_{h_2^n h_1^n} & 0 \\ m_{h_s^n h_2^n} & m_{h_1^n h_2^n} & m_{h_2^n h_2^n} & 0 \\ 0 & 0 & 0 & m_{h_a^n h_a^n} \end{pmatrix}$$

The fields corresponding to Ha are decoupled.

Neutral scalar Higgses mass range
Hs as the SM Higgs.



Charged Higgses mass range



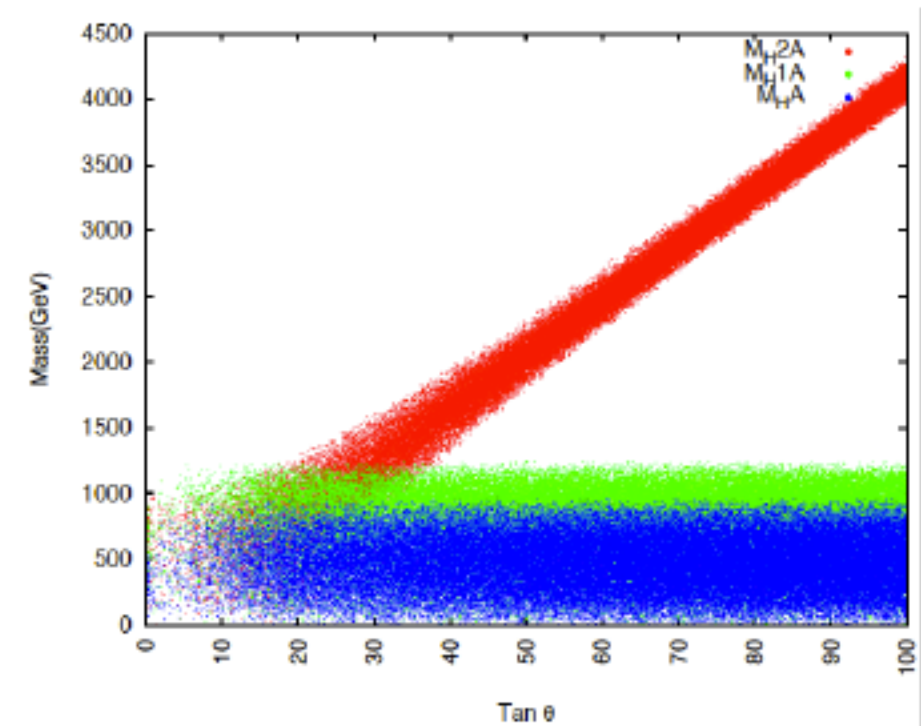
Reparametrizing the vevs as

$$v_0 = v\cos\theta$$
$$v_1 = v\sin\theta\cos\phi$$
$$v_2 = v\sin\theta\sin\phi$$

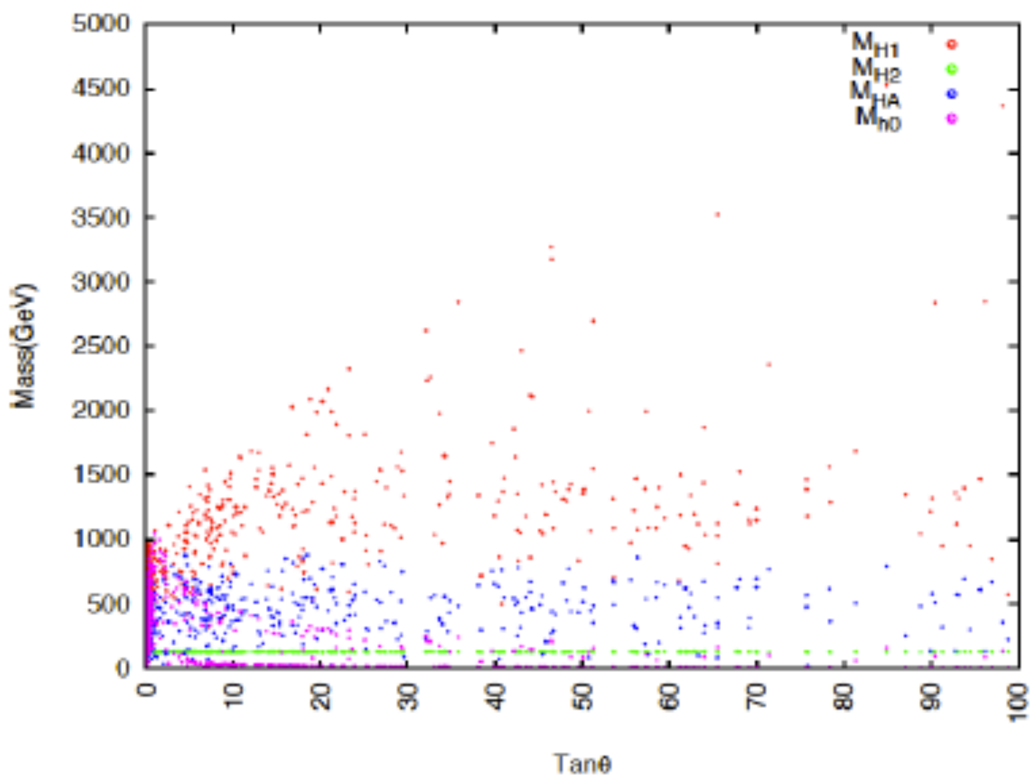
$$v_2 = \frac{1}{2}v\sin\theta \text{ and } v_3 = v\cos\theta$$

From the minimisation conditions
$$tan^2\phi = \frac{1}{3}$$

Pseudo scalar Higgses mass range

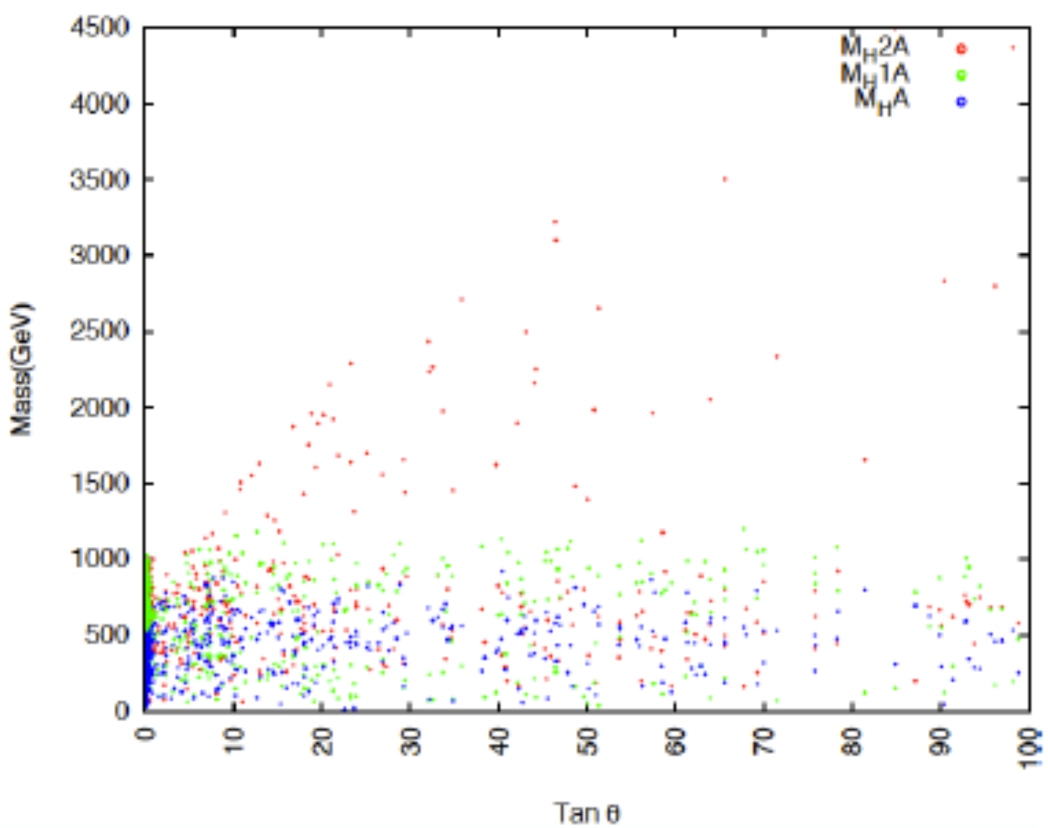


Neutral scalar Higgses mass range, scalar H2 as the SM Higgs.

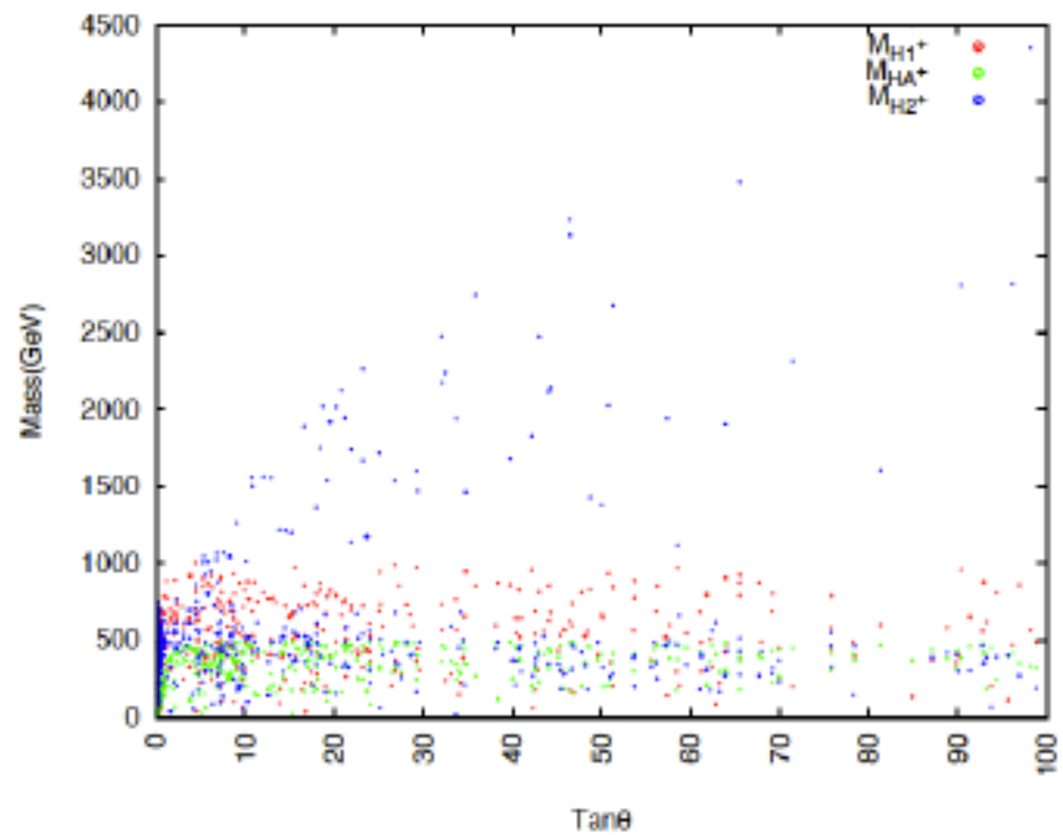


Less points, no natural decoupling limit, but most studied solution so far

Pseudo scalar Higgses mass range



Charged scalar Higgses mass range



Viable dark matter candidates

$$m_{h_a^p}^2 = \mu_2^2 + \lambda_{14} v_0^2 + 4(\lambda_{10} + \lambda_{11} - 2\lambda_{12}) v_2^2$$
$$m_{h_a^n}^2 = \mu_2^2 + \lambda_{14} v_0^2 + 4(\lambda_{10} + \lambda_{11} + 2\lambda_{12}) v_2^2.$$

Theoretical restrictions

- The potential must have a finite vacuum
- The dispersion matrix must be unitary.
- Quartic couplings must be perturbative

Experimental restrictions

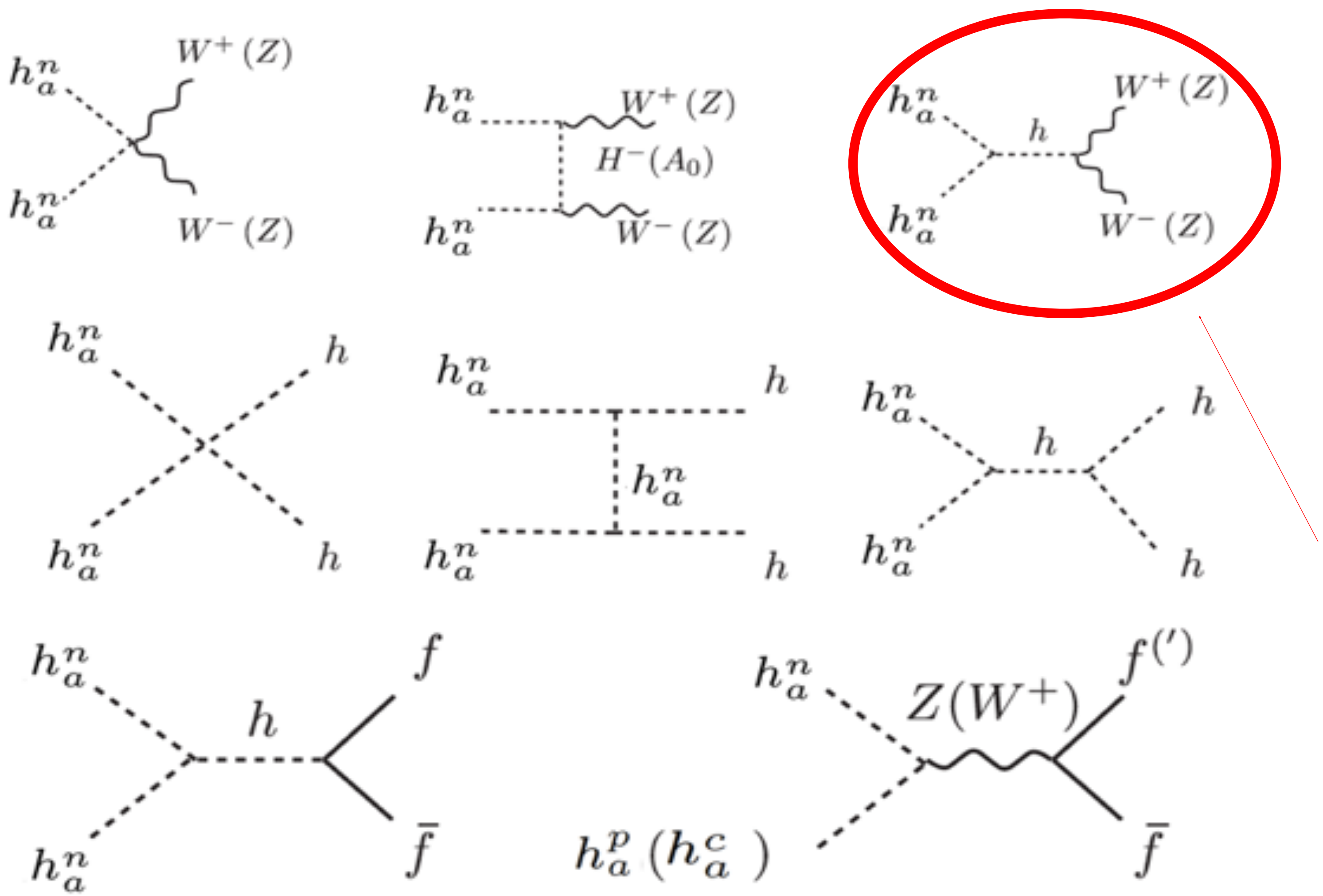
- The mass of the SM Higgs

$$m_{h_s^n} = 125.09 \pm .21\text{GeV}.$$

- The measured relic density

$$\Omega_{\text{nbm}} h^2 = 0.1186 \pm 0.0020$$

Allowed Feynman diagrams for the DM candidate

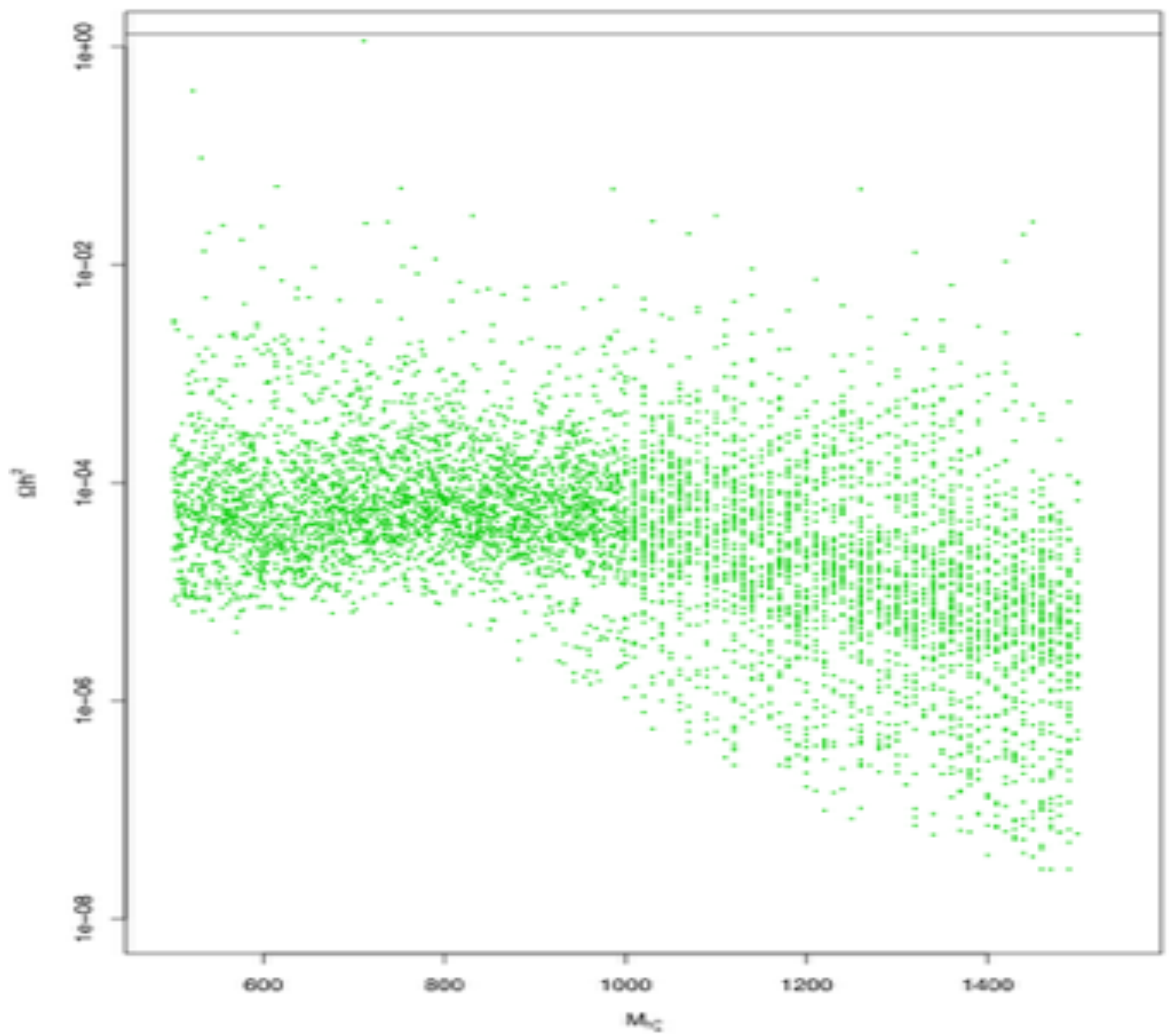


To find the relic density we need to calculate all the annihilation cross sections of the model

As a first test, we only used the circled Feynman Diagram.

This allows us to compare
with the more studied 2HDM, and get a first estimate of relic density

Relic Density scan, using MICROMEGAS.



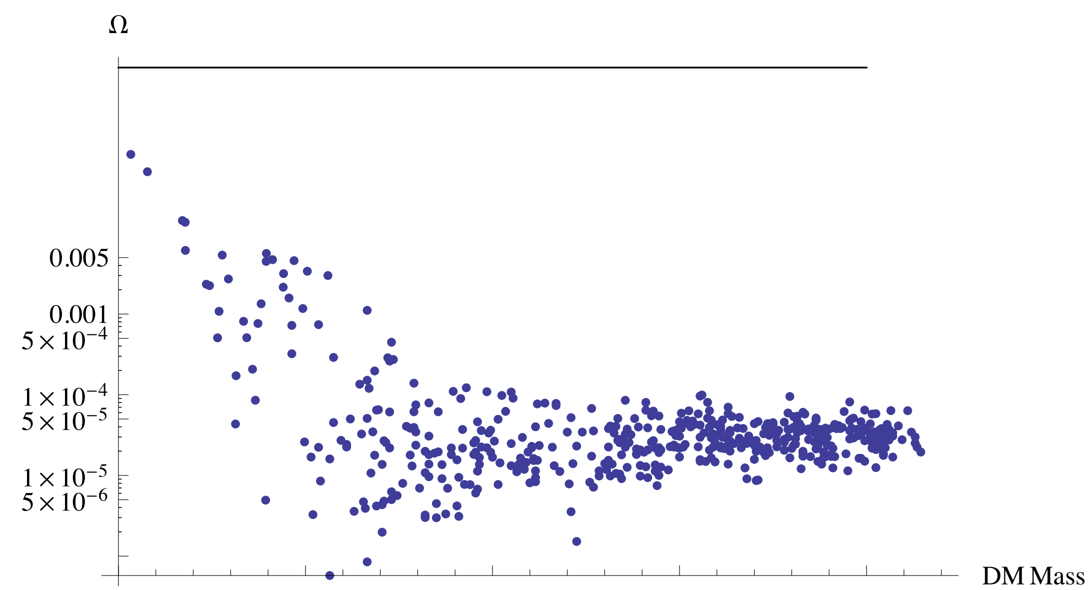
The black line represents the measured relic density, approximately 0.118. All points in this graph are below this value.

- Simplified model to check viability
- Adding all contributions: still not saturated
- Very promising, since it is below the measured Ω

G. Belanger, F. Boudjema, and A. Pukhov. micrOMEGAs : a code for the calculation of Dark Matter properties in generic models of particle interaction. In *The Dark Secrets of the Terascale*, pages 739–790, 2013.

Preliminary

- Calculation done in approximation close to SM
- Ω still not saturated
- Allows for more than one DM candidate: other scalar, right-handed neutrino…
- Allows for Sommerfeld enhancement
- Need to consider co-annihilation and decay of heavier scalars into DM candidate



What else we need to worry about…

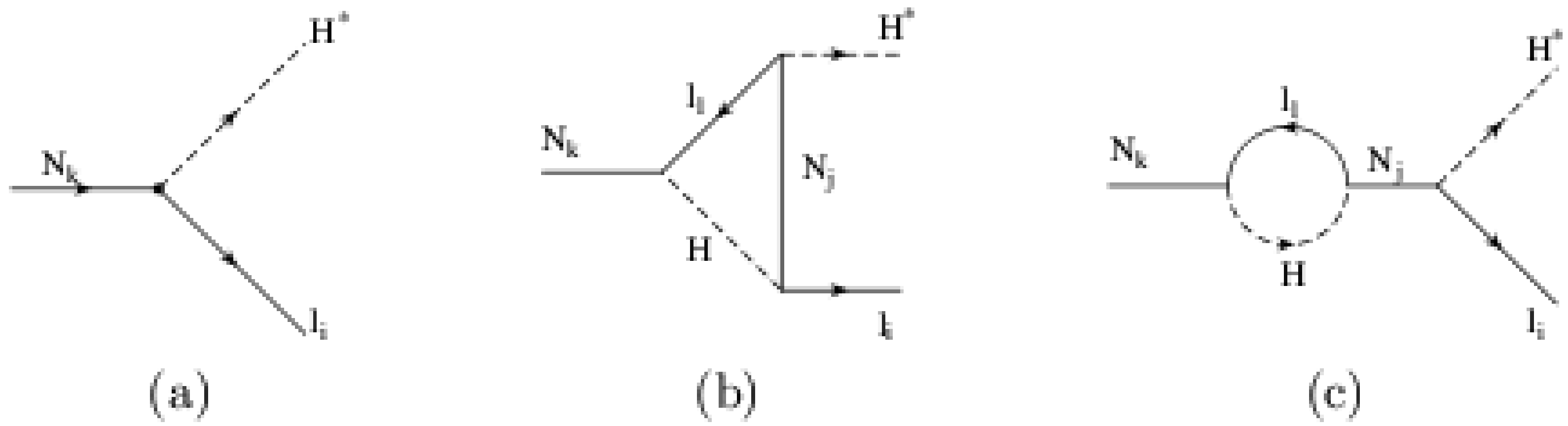
- Adding all contributions — all Feynman diagrams works still well
- Check both candidates for DM
- Possibility: one of them decaying into the other
  → more contributions
- Vacuum might not be the deepest → check for metastable solutions, i.e. vacuum tunnelling (Vevacious)
  → will constrain more the allowed parameter space

Leptogenesis in S3-3H

- The model lends itself naturally to leptogenesis and associated baryogenesis:

Heavy right handed neutrinos
Majorana neutrinos
Decay of right-handed neutrinos into the left-handed ones

$$\epsilon_1 = \frac{\sum_\alpha \Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \bar{\ell}_\alpha \overline{H})}{\sum_\alpha \Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \bar{\ell}_\alpha \overline{H})}.$$



$$\epsilon \simeq -\frac{3}{8\pi}\frac{1}{(h_\nu h_\nu^\dagger)}\sum_{i=2,3}\mathrm{Im}\{(h_\nu h_\nu^\dagger)^2_{1i}\}[f(\frac{M_i^2}{M_1^2})+g(\frac{M_i^2}{M_1^2})].$$

$$f(x)=\sqrt{x}[1-(1+x)\ln(\frac{1+x}{x})] \qquad g(x)=\frac{\sqrt{x}}{1-x}$$

Asymmetry depends on the right- and left-handed neutrino masses, as well as the phases

Mi, right handed neutrinos
hν mass matrices for Yuk couplings of Dirac neutrinos

−	+
H_S, ν_{3R}	$H_I, L_3, L_I, e_{eR}, e_{IR}.\nu_{IR}$

Table 1: Z2 assignment in the leptonic sector.

$$M_e \simeq m_\tau \begin{pmatrix} \frac{1}{\sqrt{2}}\frac{\tilde{m_\mu}}{\sqrt{1+x^2}} & \frac{1}{\sqrt{2}}\frac{\tilde{m_\mu}}{\sqrt{1+x^2}} & \frac{1}{\sqrt{2}}\frac{\sqrt{1+x^2-\tilde{m_\mu^2}}}{\sqrt{1+x^2}} \\ \frac{1}{\sqrt{2}}\frac{\tilde{m_\mu}}{\sqrt{1+x^2}} & -\frac{1}{\sqrt{2}}\frac{\tilde{m_\mu}}{\sqrt{1+x^2}} & \frac{1}{\sqrt{2}}\frac{\sqrt{1+x^2-\tilde{m_\mu^2}}}{\sqrt{1+x^2}} \\ \frac{\tilde{m_e}(1+x^2)}{\sqrt{1+x^2-\tilde{m_\mu^2}}}e^{i\delta_e} & \frac{\tilde{m_e}(1+x^2)}{\sqrt{1+x^2-\tilde{m_\mu^2}}}e^{i\delta_e} & 0 \end{pmatrix}.$$

$$\tilde{m_i} = m_i/m_\tau, \quad x^4 = (m_e/m_\tau)^4$$

- The leptonic sector has a Z2 symmetry
- Mass matrices of charged leptons and neutrinos are parameterised in terms of physical masses

Similarly for the Majorana neutrino mass matrix —
μ function of the masses, Majorana phases ϕ and Dirac phase δ

$$M_\nu = M_{\nu D}\tilde{M}^{-1}(M_{\nu D})^T = \begin{pmatrix} (\frac{1}{M_1}+\frac{1}{M_2})\mu_2^2 & (\frac{1}{M_1}-\frac{1}{M_2})\mu_2^2 & (\frac{1}{M_1}+\frac{1}{M_2})\mu_2\mu_4 \\ (\frac{1}{M_1}-\frac{1}{M_2})\mu_2^2 & (\frac{1}{M_1}+\frac{1}{M_2})\mu_2^2 & (\frac{1}{M_1}-\frac{1}{M_2})\mu_2\mu_4 \\ (\frac{1}{M_1}+\frac{1}{M_2})\mu_2\mu_4 & (\frac{1}{M_1}-\frac{1}{M_2})\mu_2\mu_4 & \frac{\mu_4^2}{M_2}+\frac{\mu_3^2}{M_3} \end{pmatrix} \tag{46}$$

Preliminary

update of arXiv:1701.07929

Solving the Boltzmann equations

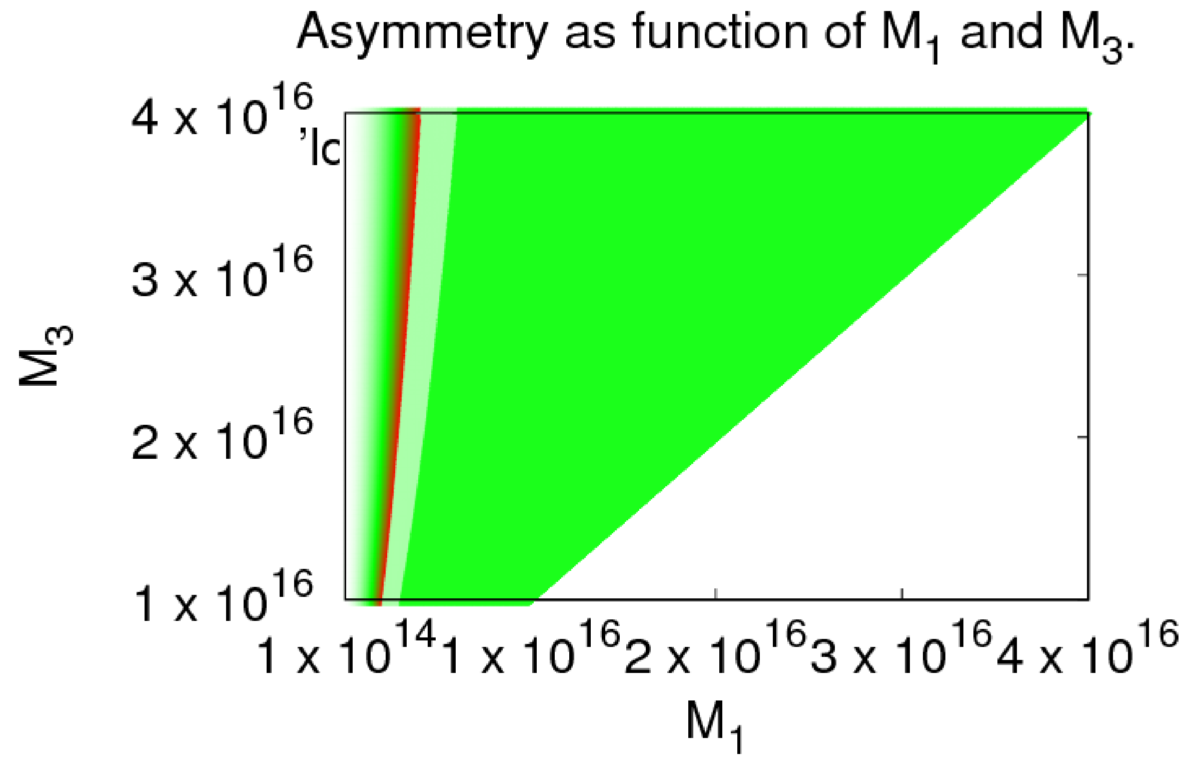
$$\epsilon = \frac{\mathrm{Im}[e^{2i\delta^*} M_2 m_3 \frac{\sqrt{M_2(m_2-m_3)(m_3-m_1)}}{\sqrt{m_3}}](f[\frac{M_3^2}{M_1^2}] + g[\frac{M_3^2}{M_1^2}])}{8\pi|M_2 m_3|} \ .$$

$$Y_B = aY_{B-L} = \frac{a}{a-1} Y_L \ , \qquad a = (8N_f + 4N_H)/(22N_f + 13N_H),$$

δ = Dirac phase, $Y_{L,B}$ = baryon, lepton asymmetry, $N_{f,H}$= number of families and Higgs doublets

Asymmetry for the degenerate case $M_1=M_2$
Only inverted hierarchy for light neutrinos possible

For the non-degenerate case it depends also
on the phases μ_{ia} , $\mu_i = |\mu_i| \mathrm{e}^{\mathrm{i}\mu_{\mathrm{ia}}}$

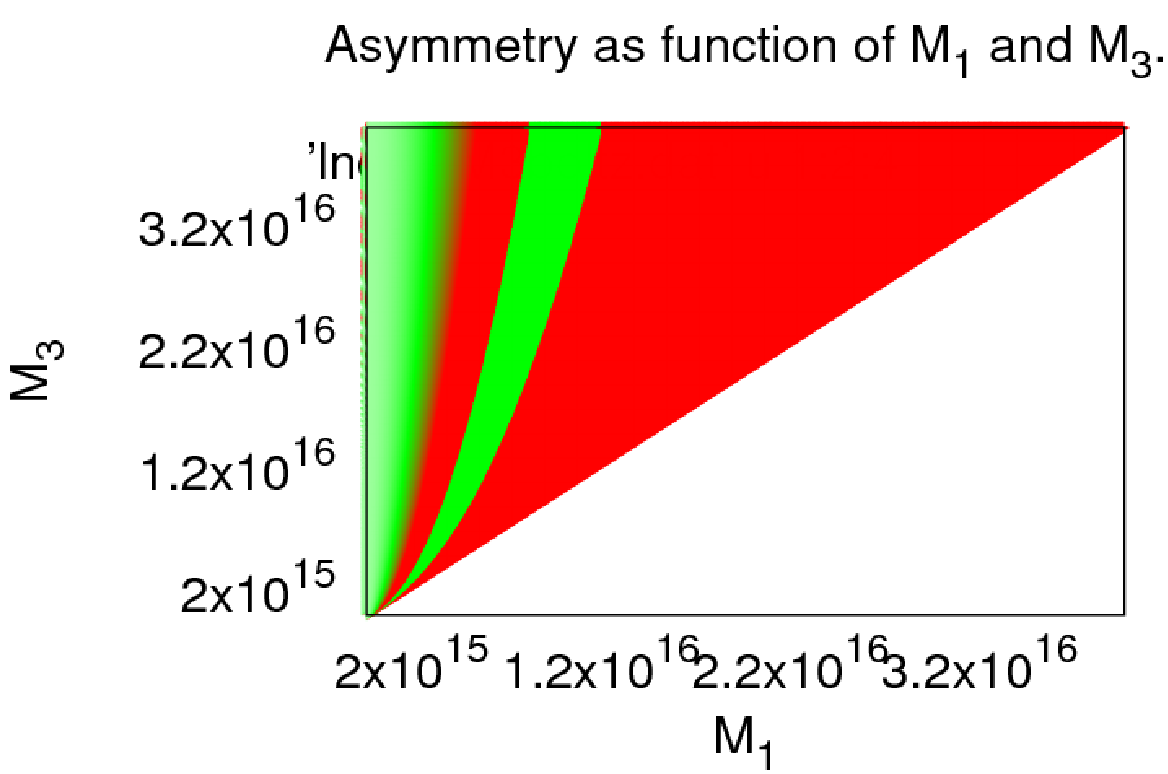


Degenerate case

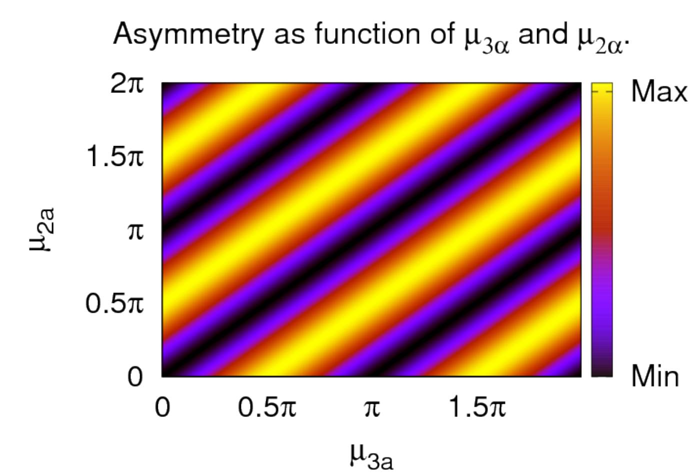
Inverted hierarchy
m1 ≈ .055 eV
m2 ≈ .056 eV
m3 ≈ .022 eV

Red - too much baryon asymmetry
Darker shades of green - more asymmetry but not yet saturated

Solution to baryon asymmetry can have R-neutino masses as low as ~10^7 GeV



Non-degenerate case



How can you go up?

- Propose a model with a similar symmetry, but at high energies

  SUSY GUT SU(5)×Q6

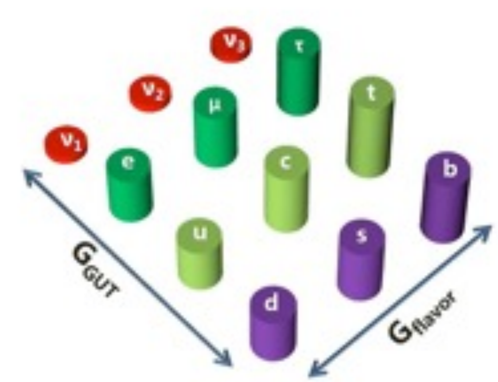
- Q6 is the double covering of S3, has similar structure

- Neutrino masses through extra singlets (right handed), U(1) or non-renormalizable interactions

- Now we start from GUT scale and go down and we recover nice features of previous model (not identical)

- CKM and PMNS ok

- Neutrino mixing angles also within experimental bounds



J.C. Gómez, F. González, M.M. (2014)

Conclusions

- Multi-Higgs models with S3 symmetry predictive, provide viable DM candidates
- Models have to be consistent from the SM point of view → extra Higgses sufficiently decoupled or inert
- Vacuum much more complicated than in SM, all checks necessary: stability, perturbative unitarity
- 4H-3S (based on 3H-3S) model promising:
  - explains well masses and mixings in quark and lepton sectors
  - can provide with two promising DM candidates
  - enough leptogenesis to explain baryogengesis (3H-3S) A.Alvarez & M.M
  - Possible to have more DM candidates in the R-neutrino sector, not yet explored