Dark Matter Stability From FLAvor SYmmetry

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Bruxelles, *1st March 2013*


FLASY 2011
1st Workshop on Flavor Symmetries and consequences in Accelerators and Cosmology
11 – 14 July 2011, Valencia (Spain)
https://ific.uv.es/~flasy2011/
FLASY'12
2nd WORKSHOP
ON FLAVOR SYMMETRIES
30 JUNE 2012 – 4 JULY 2012,
Dortmund, Germany
Topics include:
Flavor dynamics & local flavor symmetries,
CP violation, Hot observables (ΔA_CP, θ_13, μ→eγ, B_s-B_s),
Discrete flavor symmetries, SUSY & flavor, Extra dimensions & flavor,
New ideas!
http://flasy12.tu-dortmund.de Contact: flasy12@physik.tu-dortmund.de
Int. Advisory Board: G. Altarelli, A. Buras, T. W. Kephart, M. Lindner, E. Ma, S. Morisi, Y. Nir, J. W.F. Valle
Organizers (TU Dortmund): C. Hambrock, G. Hiller, M. Jung, P. Leser, H. Päs, S. Schacht, I. de Medeiros Varzielas
FLASY 13
Niigata 1 July - 5 July
Global neutrino data
Flavor symmetries
GUT
Dark Matter
Collider phenomenology
0nubb
Greenland
Iceland
Sweden
Norway
United Kingdom
Germany
France
Spain
Italy
Ukraine
Kazakhstan
Russia
Mongolia
China
Japan
Turkey
Afghanistan
Iraq
Iran
Pakistan
Saudi Arabia
Algeria
Libya
Egypt
Mali
Niger
Chad
Sudan
Nigeria
Venezuela
Colombia
DR Congo
Brazil
Peru
Bolivia
Angola
Namibia
Botswana
Madagascar
Indian Ocean
South Atlantic Ocean
Chile
South Africa
Argentina
Indonesia
Australia

DM life-time **>** age of the universe

stable DM

decaying DM

$$Z_2 : \begin{cases} \mathrm{DM} \longrightarrow -\,\mathrm{DM} \\ \mathrm{SM} \longrightarrow +\,\mathrm{SM} \end{cases}$$

Z2 is typically imposed by hand

It seems there are no motivations to assume an
ad-hoc symmetry

since in the SM there are stable particles
without introducing any ad hoc symmetry
photon, electron, neutrino, proton

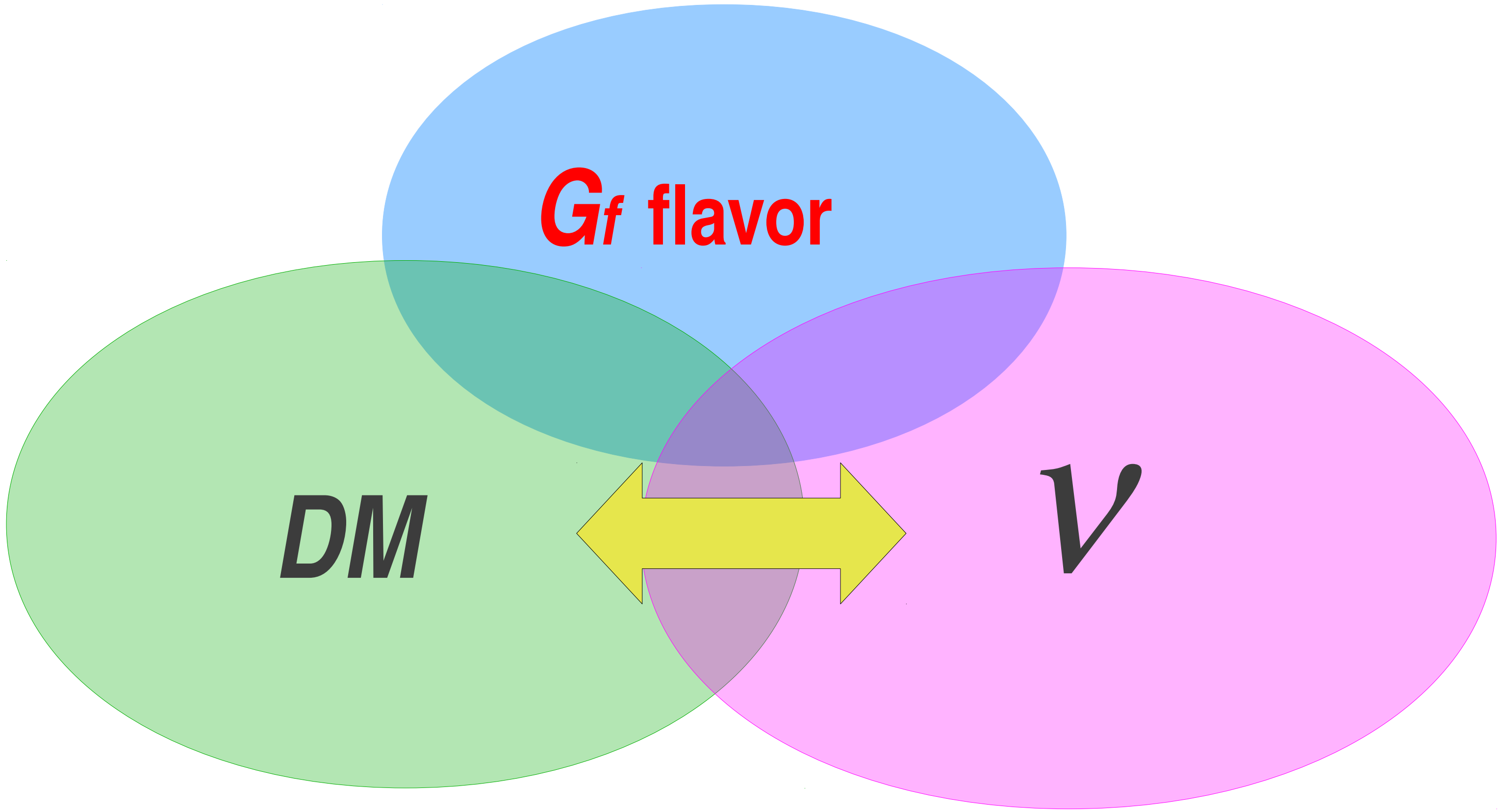
possible origin of DM stability :

- R - parity in MSSM (LSP)

- $U(1)_{B-L}$ from GUT

Hambye 1012.4587

DM stability from flavor symmetry



Outline of the talk

- Flavor problem

- Flavor symmetry: TBM & discrete groups

- Stability of DM from flavor symmetry breaking

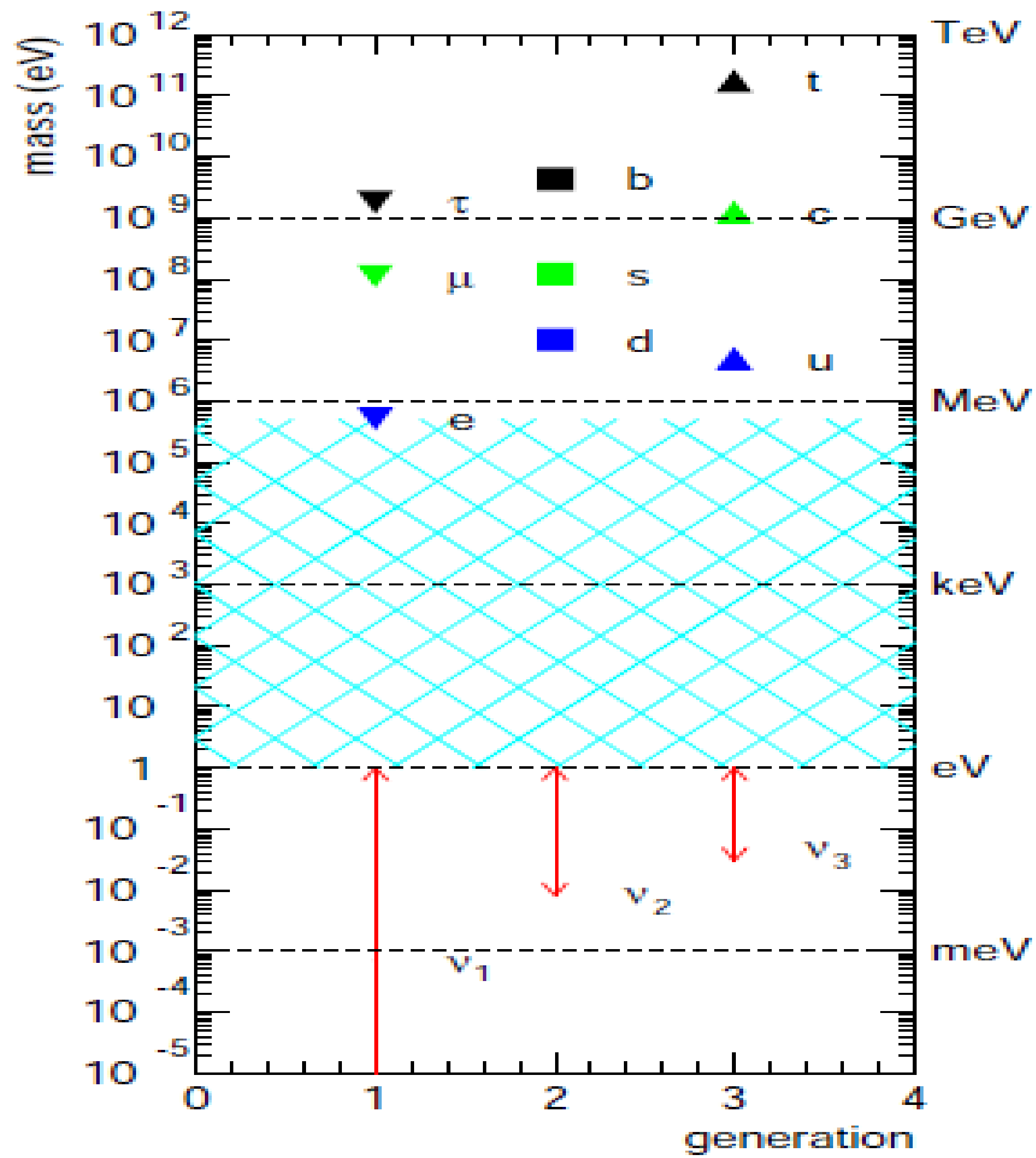
- Examples

-Conclusions

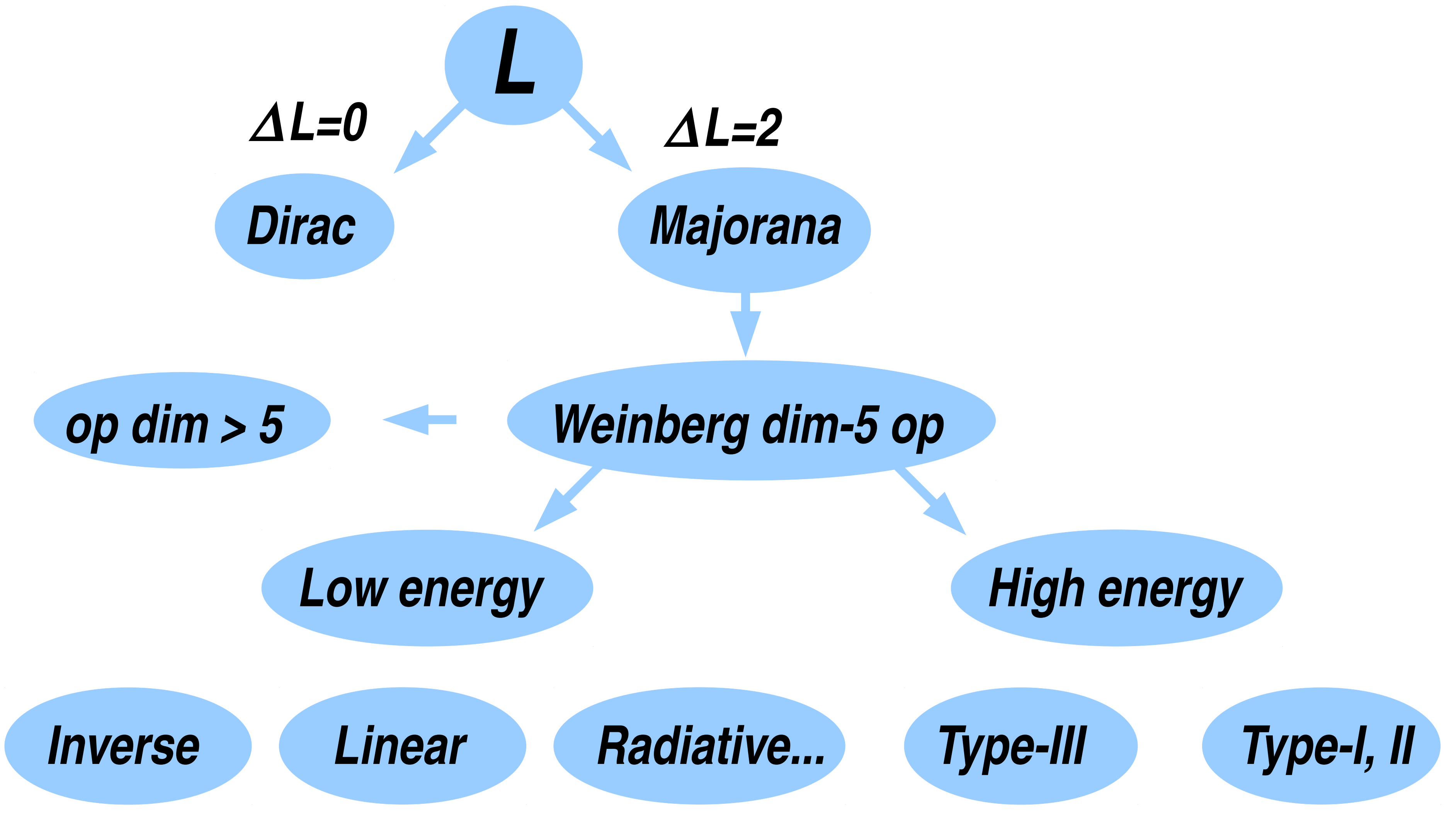
flavor problem
&
flavor symmetry

Fermion mass hierarchies

André de Gouvêa

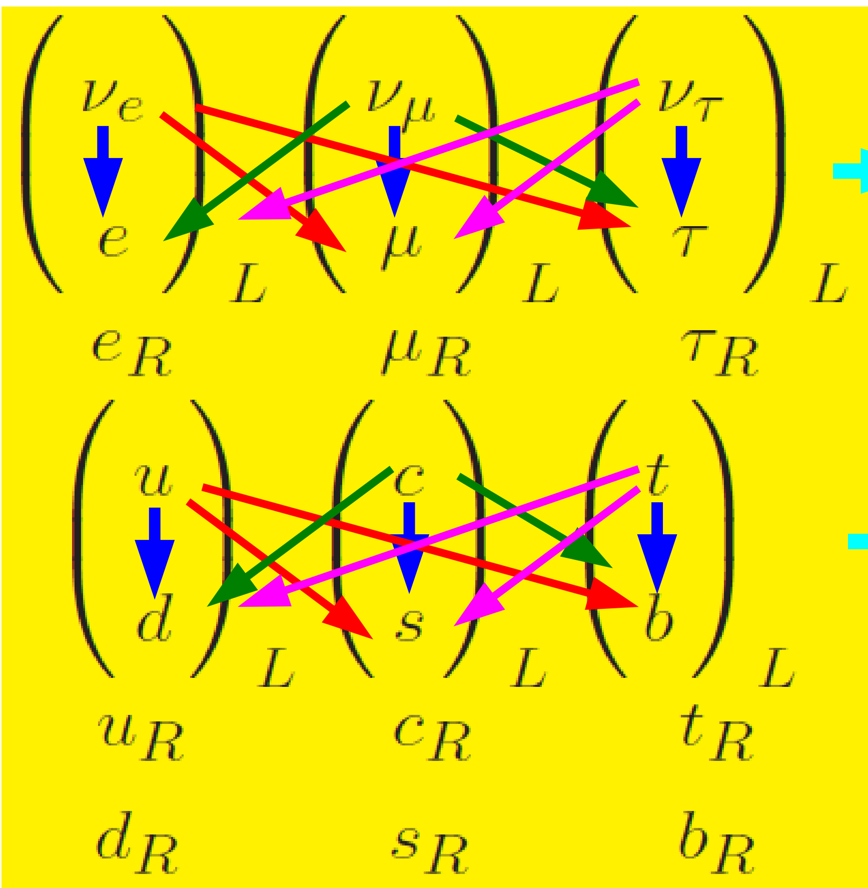


Origin of neutrino mass



lepton vs quark mixing

quarks as well as leptons mix



quark/lep mixing very different

$$\begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0,178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

$$\begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.008 & 0.040 & 0.999 \end{pmatrix}$$

The flavor problem

- why three families?
- why fermion mass hierarchies?

  in the SM there is no reason to have very different masses
- why quarks and leptons mix?
- why quarks/lepton mixing are so different?

- neutrino are Dirac or Majorana?
- what is the absolute neutrino mass scale?
- what is the neutrino mass hierarchy?
- CP is violated in the lepton sector?

Different approaches to flavor problem

- correlations between mixing and masses like in texture zero

- grand unification

- flavor symmetries, abelian, <u>non-abelian</u>, continue, <u>discrete</u>

- ……..

- it is not a problem: no reason why $m_e << m_{top}$

The flavor symmetry $SU_c(3) \times SU_L(2) \times U_Y(1) \times G_f$

horizontal symmetry like *SU(3) – triplets*

vertical gauge symmetry

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$e_R \quad \mu_R \quad \tau_R$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R$$

Flavor symmetry & flavor problem: status

The flavor *"problem"* is still there:

- why three families? *No idea – irrep = 3 of flavor symm*
- why fermion mass hierarchies? *No idea – FN?*
- why quarks and leptons mix? *May be flavor symm breaking*
- why quarks/lepton masses & mixing are so different?

  May be neutrino are Majorana (seesaw?) & flavor symm

We have many good models for quarks & lepton mixing: *too many!*

Most of these models are phenomenologically equivalent

May be 0nubb, LVF, LHC,....,GUT, DM help us to distinguish

In a quite near future experiments could tell us if

Neutrino are Majorana, their mass hierarchy and CP phase,

Moreover we will have more info about Higgs sector

*Will this fix the neutrino sector **??***

TBM & discrete groups

Tri-Bimaximal Mixing (TBM)

For about 10 years data have biased us towards *TBM*

$$U_{\rm HPS} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Harrison,Perkins, Scott 2002

trimaximal

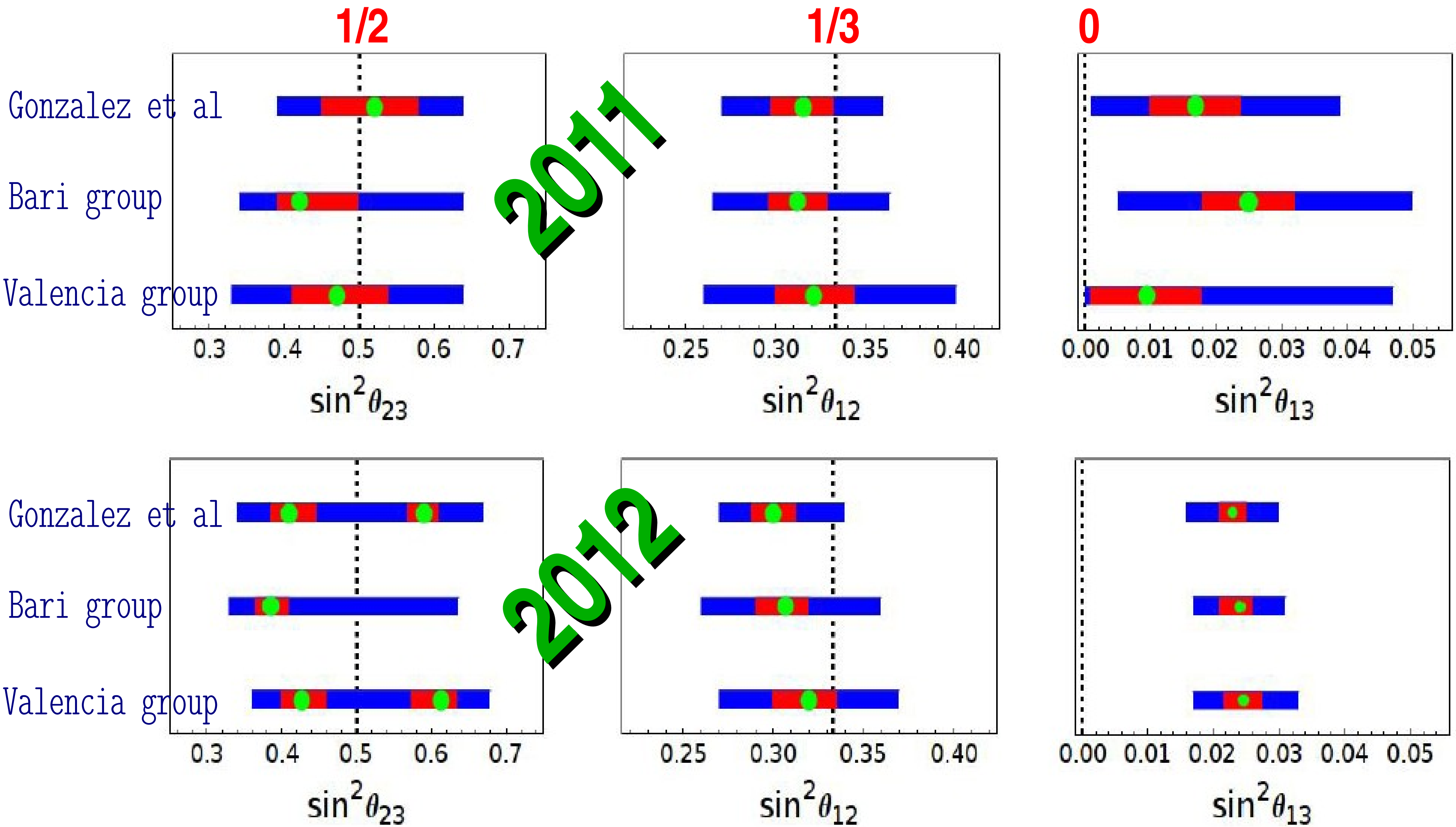
$$\nu_2 = \frac{1}{\sqrt{3}}(\nu_e + \nu_\mu + \nu_\tau)$$

Bimaximal

$$\nu_3 = \frac{1}{\sqrt{2}}(-\nu_\mu + \nu_\tau)$$

$$\sin^2\theta_{23} = 0.5 \qquad \sin^2\theta_{12} = 1/3 \qquad \sin^2\theta_{13} = 0$$

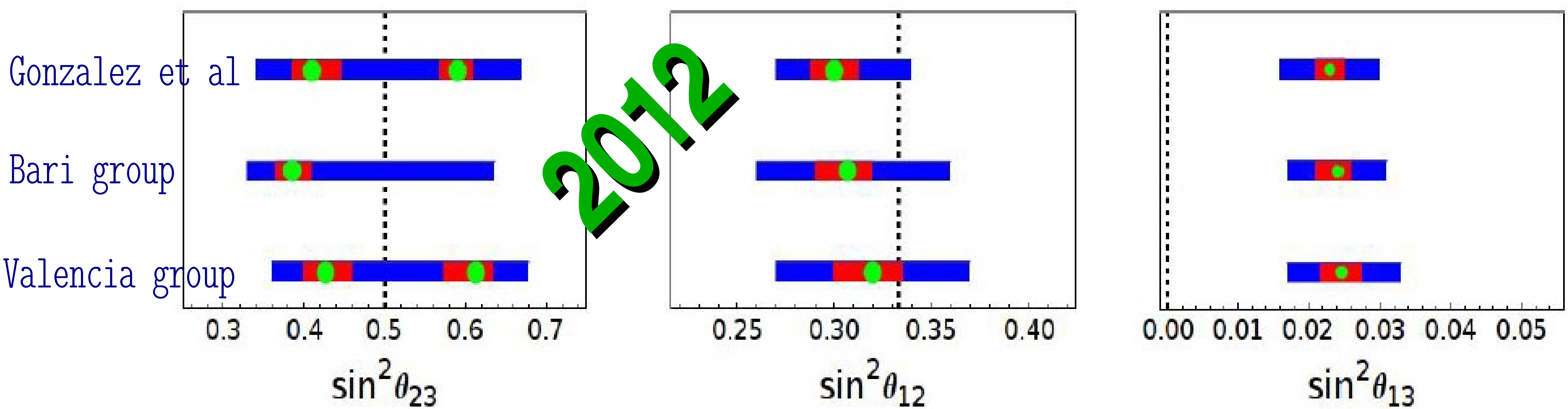
2011 vs 2012 neutrino mixing data



TBM is ruled out!

$$U_{HPS} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

- θ_{13} is not zero
- θ_{23} is not maximal @ 1*sigma*



G_f

Deviation of TBM

Different ansatz:

trimaximal, tetramaximal, symmetric mixing, hexagon mixing, bimaximal, golden,..

Albright,Dueck,Rodejohann 1004.2798

Bi-large

Boucenna,M,Tortola,Valle 1206.6678

Bi-Trimaximal

King, Luhn, Stuart 1207.5741

Anarchy?

Hall,Murayama,Weiner,PRL
Altarelli, Feruglio,Masina,JHEP
Gouvea , Murayama 1204.1249

Discrete groups & TBM

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	$D_{15},\ D_5 \times Z_3,\ D_3 \times Z_5$

A4 Babu, Ma, Valle PLB552
Altarelli, Feruglio NPB720

S3 Grimus, Lavoura, JHEP0904
Mohapatra,Nasri,Yu PLB639

S4 Lam PRL101
Bazzocchi, Morisi PRD80

T' Feruglio,Hagedorn,Lin,Merlo NPB775
Car, Frampton
Aranda,Carone,Lebed PLB474

D(27) Medeiros,King,Ross PLB648

for a review of the properties of these groups see
Ishimori,Kobayashi,Ohki,Okada, Shimizu,Tanimoto 1003.3552

Introduction to discrete groups

A group **G={A,B,C,...}** which consist of a finite number of elements **g** is a *finite group if*

- the set is close with respect to the composition law
- associative
- cancelling rule: $A\,X = B\,X$ and $Y\,A = Y\,B$ ⇒ $A = B$

To each finite group corresponds a multiplication table

g=6	I	A	B	C	D	E
I	I	A	B	C	D	E
A	A	B	I	E	C	D
B	B	I	A	D	E	C
C	C	D	E	I	A	B
D	D	E	C	B	I	A
E	E	C	D	A	B	I

Not all the product are independent:

A C = E, C B = E, B B = A, C B = E, A E = D ➡ C A = D

It exists a set of **elements** and a set of **independent relations** associated to each multiplication table

Generator of the groups

$$I, A, A^2, C, AC, CA$$

		I	A	B	C	D	E
$I=$	I	I	A	B	C	D	E
$A=$	A	A	B	I	E	C	D
$A^2=$	B	B	I	A	D	E	C
$C=$	C	C	D	E	I	A	B
$CA=$	D	D	E	C	B	I	A
$AC=$	E	E	C	D	A	B	I

Set of elements

$$A\,,\ C$$

Set of relations

$$A^3 = C^2 = (AC)^2 = I$$

Generator of the groups

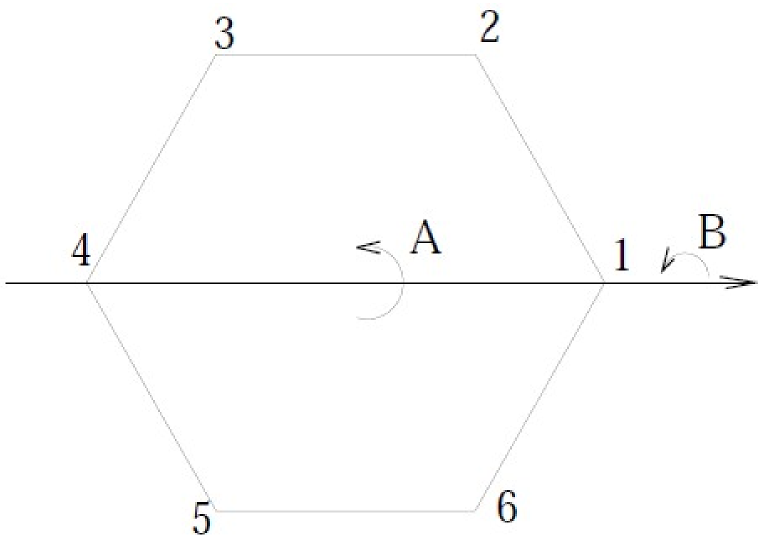
Every finite group is completely determinate from

- a set of generators
- a set relations

examples →

Dihedral Dn groups

Consider the lamina

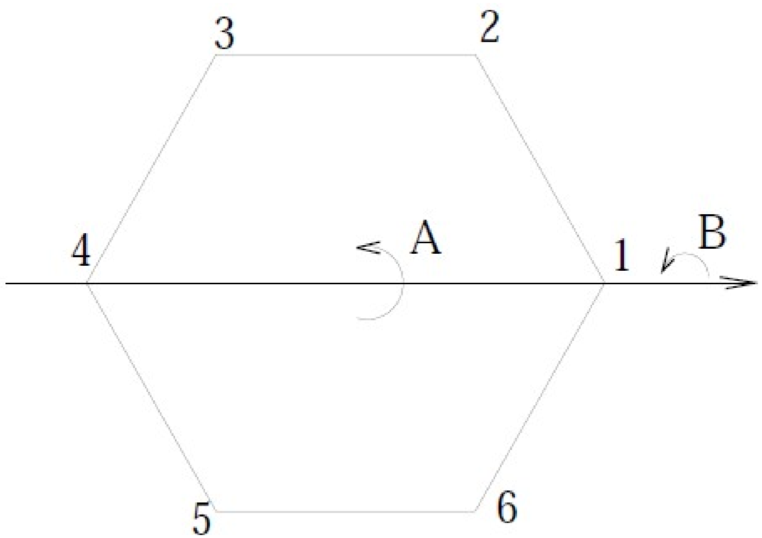


It is invariant under *n*-rotations (*A* generator of rotations)

$$0,\ \frac{2\pi}{n},\ 2\,\frac{2\pi}{n},\ \ldots,\ (n-1)\,\frac{2\pi}{n} \quad \Rightarrow \quad I,\ A,\ A^2,\ \ldots A^{n-1}; \quad A^n = I$$

Dihedral Dn groups

Consider the lamina

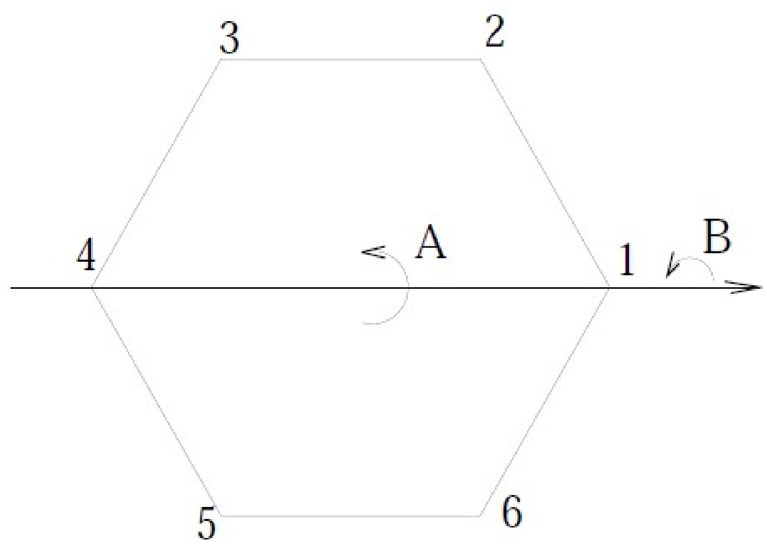


We can reflect the lamina around an axis (*B* generator of the reflaction)

$$B \quad \Rightarrow \quad B^2 = I$$

Dihedral Dn groups

Consider the lamina

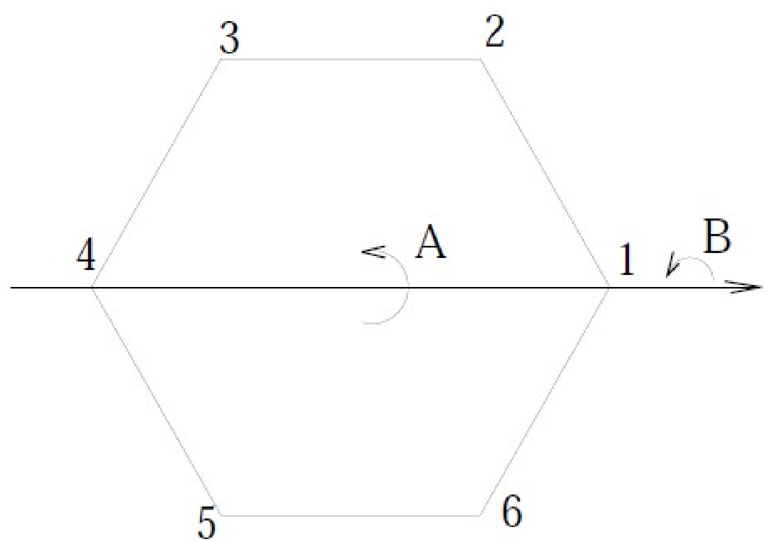


$$\text{reversing} + \text{rotate} \equiv (\text{rotate})^{-1} + \text{reversing}$$

$$\Rightarrow \quad A\,B = B\,A^{-1} \Rightarrow (AB)^2 = I$$

Dihedral Dn groups

Consider the lamina



All the transformations (elements of the group) are

$$B^{\alpha}\, A^{\beta} \quad (\alpha = 0, 1; \beta = 0, 1, .., n-1)$$

generators
get of relations

$$A^n = B^2 = (AB)^2 = I$$

Stability of DM
from
flavor symmetry breaking

We need:

1) $G_f \longrightarrow Z_N \;\; (Z_2)$

2) $r = (r1, r2, r3, \ldots.) \longrightarrow$ at least one component of ***r*** is <u>*odd*</u> under Z2

A4 group

12 elem.

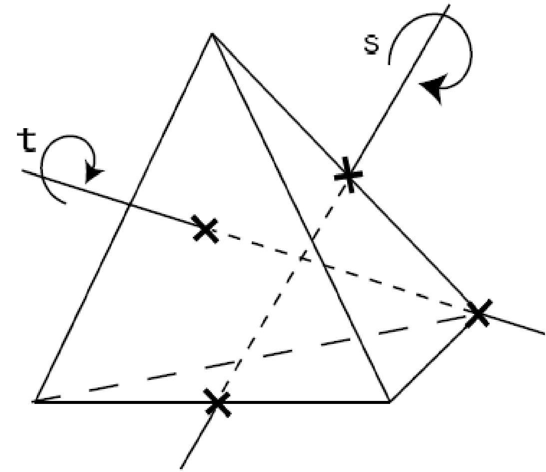
C1: I

C2: **T**, ST, TS, STS

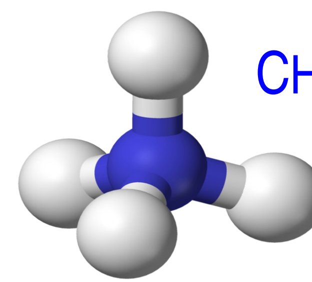
C3: TT, STT,TTS,TST

C4: **S**, TTST, TSTT

⟺ Isomorphic to group of thetraedron rotations



12 rotations



CH4

Smallest group with triplet irrep 3

1) $G_f \longrightarrow Z_2$

Generators of A4

$$S^2 = T^3 = (ST)^3 = 1$$

S generator of Z_2

Z_3

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

$$S \langle \eta \rangle = \langle \eta \rangle \quad \Longleftrightarrow \quad A_4 \xrightarrow{\text{spontaneously}} Z_2$$

$$S^2 = T^3 = (ST)^3 = 1$$

generator of Z_2

$$S = \begin{pmatrix} +1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \qquad \langle \eta \rangle \sim (1, 0, 0)$$

2) r = (r1, r2, r3,....) $\longrightarrow$ at least one component of ***r*** is *odd* under Z2

A_4 irrep : ***1, 1', 1'', 3***

Z_2 : $3 = (a_1, a_2, a_3) \longrightarrow (+a_1, -a_2, -a_3)$

The field in a_2 or a_3 can be our DM candidate

How a 3 transforms under the Z2 of A4

$$S^2 = T^3 = (ST)^3 = 1 \quad \Longleftrightarrow \quad S = \begin{pmatrix} +1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$\begin{pmatrix} +1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \cdot \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} = \begin{pmatrix} +\eta_1 \\ -\eta_2 \\ -\eta_3 \end{pmatrix}$$

can be our DM candidate

2) r = (r1, r2, r3,....) $\longrightarrow$ at least one component of ***r*** is *odd* under Z2

A_4 irrep : ***1, 1', 1'', 3***

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

are *even* under Z2 DM can not be a singlet of A4

The Model:
discrete dark matter

Altarelli, Feruglio Nucl.Phys. B720 (2005)

A4 is spontaneously broken in

Z3 in the charged sector

T: (1,1,1)

Z2 in the neutrino sector

S: (1,0,0)

TBM

A4 **totally broken!**

Hirsch, Morisi, Peinado, Valle, PRD82 (10')

A4 is spontaneously broken in

Z2 in the charged sector

Z3 broken

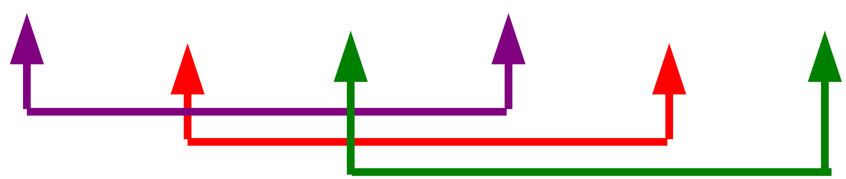
Z2 in the neutrino sector

~~TBM~~

unbroken Z2 stabilize the DM

Matter assignment: charged sector

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	$\hat{H}$	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



$1' \times 1' = 1''$, $1' \times 1'' = 1$, $1'' \times 1'' = 1'$ etc.

charged leptons in *singlets* of A4 → charged lep mass matrix *diagonal* and *Z2* invariant

The model

DM

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	$\hat{H}$	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

$$3 \times 3 = 1 + 1' + 1'' + 3 + 3$$

$$y_1^\nu L_e (N_T \eta)_1 + y_2^\nu L_\mu (N_T \eta)_{1''} + y_3^\nu L_\tau (N_T \eta)_{1'}$$

The model

DM

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	$\hat{H}$	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

1 x 1 x 3 is not A4 invariant

$$3 \times 3 = 1 + 1' + 1'' + 3 + 3$$

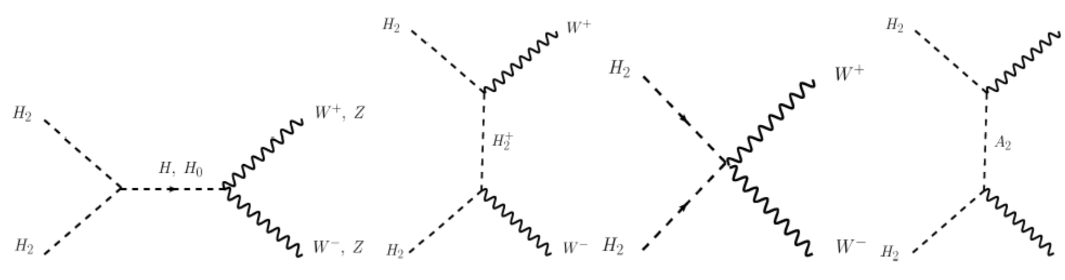
⇒ DM does not couple to charged leptons

DM couplings

	L_1	N_3	η_2
A4	1	3	3
Z2	+	–	–

Higgs portal $\eta^\dagger \eta H^\dagger H$

gauge



$\langle \eta^0_{2,3} \rangle = 0 \quad m_N \gg m_{\eta_2}$ → DM stability

Inert DM – Higgs portal

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

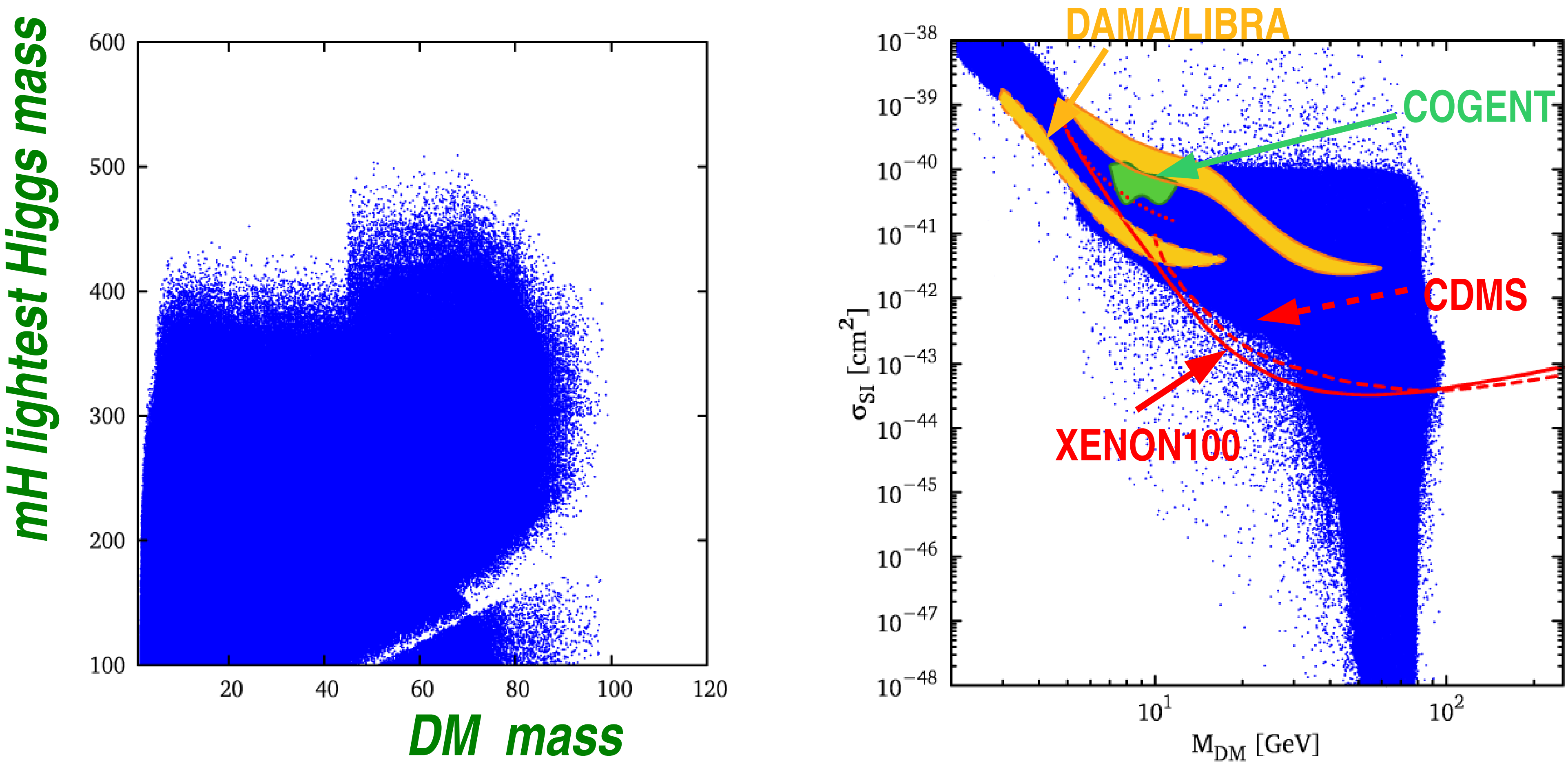
Barbieri, Hall, Rychkov, PRD74 (06')
Lopez Honorez, Nezri, Oliver, Tytgat, JCAP 0702 (07')
Gustafsson, Lundstrom, Bergstrom, Edsjo, PRL99 (07')
Lundstrom, Gustafsson, Edsjo PRD79 (09')
Andreas, Arina, Hambye, Ling,Tytgat, PRD82 (10')
Chu, Hambye, Tytgat, JCAP1205 (12')
Gustafsson, Rydbeck, Lopez-Honorez, Lundstrom PRD86 (12')

Four Higgs in the DDM

$$\begin{aligned} V \;=\;& \mu_\eta^2 \eta^\dagger\eta + \mu_{\hat{H}}^2 \hat{H}^\dagger\hat{H} + \lambda_1[\hat{H}^\dagger\hat{H}]_1^2 + \lambda_2[\eta^\dagger\eta]_1^2 + \lambda_3[\eta^\dagger\eta]_{1'}[\eta^\dagger\eta]_{1''} \\ +\;& \lambda_4[\eta^\dagger\eta^\dagger]_{1'}[\eta\eta]_{1''} + \lambda_{4'}[\eta^\dagger\eta^\dagger]_{1''}[\eta\eta]_{1'} + \lambda_5[\eta^\dagger\eta^\dagger]_1[\eta\eta]_1 + \lambda_6([\eta^\dagger\eta]_{3_1}[\eta^\dagger\eta]_{3_1} + h.c.) \\ +\;& \lambda_7[\eta^\dagger\eta]_{3_1}[\eta^\dagger\eta]_{3_2} + \lambda_8[\eta^\dagger\eta^\dagger]_{3_1}[\eta\eta]_{3_2} + \lambda_9[\eta^\dagger\eta]_{1'}[\hat{H}^\dagger\hat{H}] + \lambda_{10}[\eta^\dagger\hat{H}]_{3_1}[\hat{H}^\dagger\eta]_{3_1} \\ +\;& \lambda_{11}([\eta^\dagger\eta^\dagger]_1\hat{H}\hat{H} + h.c.) + \lambda_{12}([\eta^\dagger\eta^\dagger]_{3_1}[\eta\hat{H}]_{3_1} + h.c.) + \lambda_{13}([\eta^\dagger\eta^\dagger]_{3_2}[\eta\hat{H}]]_{3_1} + h.c.) + \lambda_{14}([\eta^\dagger\eta]_{3_1}\eta^\dagger\hat{H} + h.c.) \\ +\;& \lambda_{15}([\eta^\dagger\eta]_{3_2}\eta^\dagger\hat{H} + h.c.) \end{aligned}$$

Boucenna, Hirsch, Morisi, Peinado, Taoso, Valle, JHEP 1105 (11')

Relic density – direct detection



Boucenna, Hirsch, Morisi, Peinado, Taoso, Valle, JHEP 1105 (11')

Neutrino phenomenology

$$m_D = \begin{pmatrix} x_1 & 0 & 0 & x_4 \\ x_2 & 0 & 0 & 0 \\ x_3 & 0 & 0 & 0 \end{pmatrix}, \quad M_R = \begin{pmatrix} M_1 & 0 & 0 & 0 \\ 0 & M_1 & 0 & 0 \\ 0 & 0 & M_1 & 0 \\ 0 & 0 & 0 & M_2 \end{pmatrix}$$

$$m_\nu = -m_{D_{3\times 4}} M^{-1}_{R_{4\times 4}} m^T_{D_{3\times 4}} \equiv \begin{pmatrix} y^2 & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{pmatrix}$$

IH : $m_3 = 0$

0.03 eV< 0nubb <0.05 eV

$$V_3 \sim \begin{pmatrix} 0 \\ -b/c \\ 1 \end{pmatrix}$$

$\theta_{13} = 0$

Hirsch, Morisi, Peinado, Valle, PRD (10')	Discrete DM *(DDM)*
Boucenna, Hirsch, Morisi, Peinado, Taoso, Valle JHEP (11')	relic density, detection
Meloni, Morisi, Peinado, PLB (11')	different neutrino pheno
Meloni, Morisi, Peinado, PLB (11')	A4 $\rightarrow$ D4
Adelhart Toorop, Bazzocchi, Morisi, NPB (12')	quark sector
Boucenna, Morisi, Peinado, Shimizu, Valle, PRD (12')	A4 $\rightarrow$ Delta(54)

Kajiyama, Okada NPB(11), Adulpravitchai, Batell, Pradler PLB(11), Kajiyama, Okada, Toma EPJC(11)
Batell, Pradler, Spannowsky JHEP(11), Lavoura JPG(12), Kajiyama, Kannike, Raidal PRD(12),
Eby, Frampton PLB(12), Lovrekovic (12)

Is it possible to assign ***L*** to ***irrep > 1*** ?

	L_2	N_1	η_3
A4	***3***	***3***	***3***
Z2	$-$	$+$	$-$

DM can decays into light neutrinos !

We search for a group *G* that contains at least ***two irrep***

$$r_a \quad r_b \quad \dim(r_{a,b}) > 1$$

all its components are invariant under a subgroup Z_N of *G*

at least one of its component transforms with respect to Z_N

DM candidate

D(54) has a subgroup → ***Z3 x Z3***

Boucenna,M,Peinado,Shimizu,Valle *PRD (12)*

$$a^3 = a'^3 = I$$

	$\mathbf{1}_+$	$\mathbf{1}_-$	$\mathbf{2}_1$	$\mathbf{2}_2$
a	1	1	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} \omega^2 & 0 \\ 0 & \omega \end{pmatrix}$
a'	1	1	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} \omega^2 & 0 \\ 0 & \omega \end{pmatrix}$

Ishimori et al., Prog.Theor.Phys.Suppl. 183

Invariant under Z3 x Z3

DM: transforms under Z3 x Z3

	$\overline{L}_e$	$\overline{L}_D$	e_R	l_D	H	χ	η	Δ
$SU(2)$	2	2	1	1	2	2	2	3
$\Delta(54)$	$\mathbf{1}_+$	$\mathbf{2}_1$	$\mathbf{1}_+$	$\mathbf{2}_1$	$\mathbf{1}_+$	$\mathbf{2}_1$	$\mathbf{2}_3$	$\mathbf{2}_1$

$$\mathbf{2}_\mathrm{k} \times \mathbf{2}_\mathrm{k} = \mathbf{1}_+ + \mathbf{1}_- + \mathbf{2}_\mathrm{k}$$

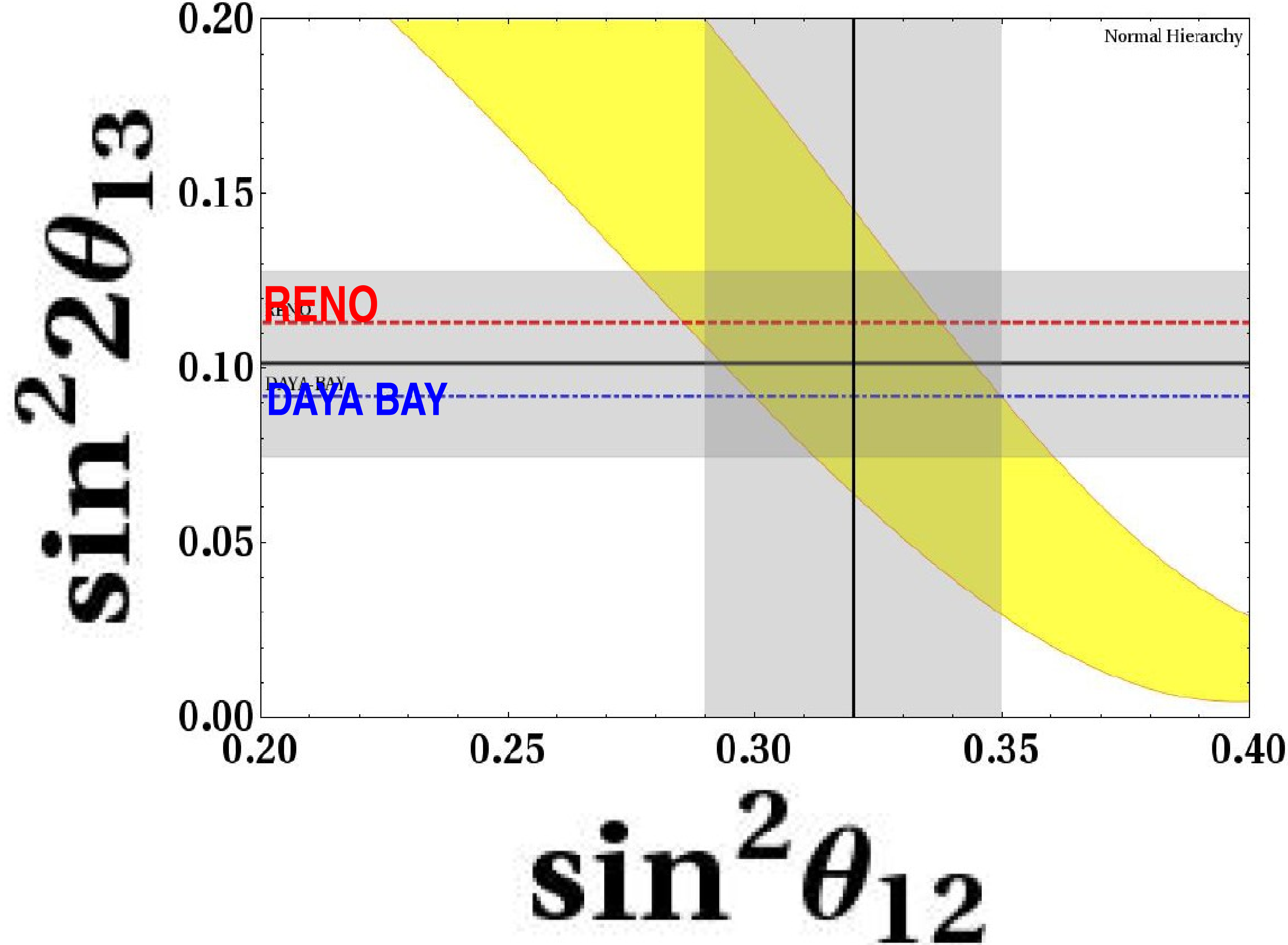
$$\mathbf{2}_1 \times \mathbf{2}_2 = \mathbf{2}_3 + \mathbf{2}_4$$

Stable

Inert: no coupling with fermions

$$\mathcal{L}_\ell = y_1 \overline{L}_e e_R H + y_2 \overline{L}_e l_D \chi + y_3 \overline{L}_D e_R \chi + y_4 \overline{L}_D l_D H + y_5 \overline{L}_D l_D \chi$$

$$\mathcal{L}_\nu = y_b \overline{L}_D \overline{L}_D \Delta + y_a \overline{L}_D L_e \Delta$$

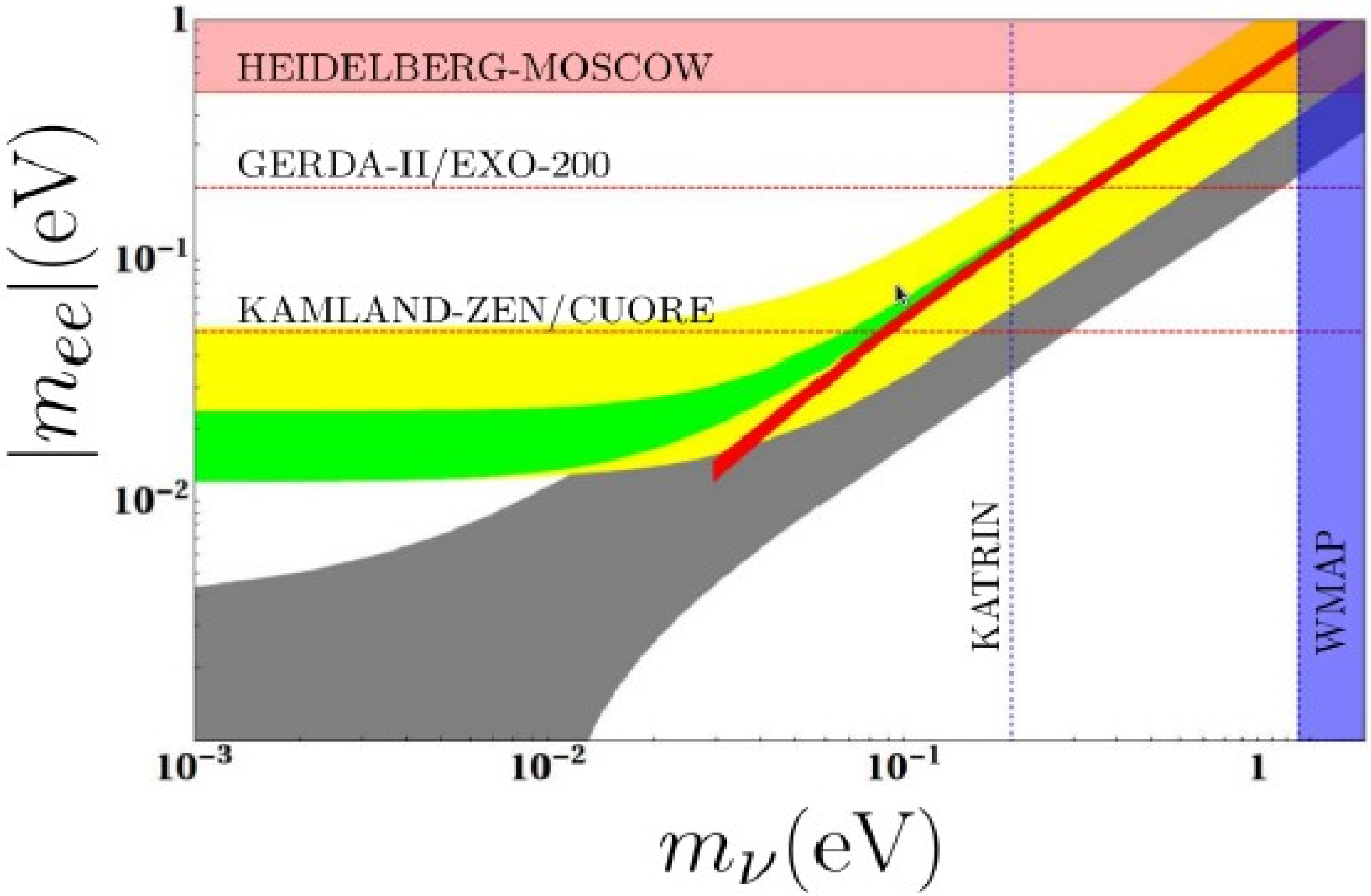


Normal Hierarchy
RENO
DAYA BAY
0.20
0.15
0.10
0.05
0.00
0.20
0.25
0.30
0.35
0.40
$\sin^2 2\theta_{13}$
$\sin^2\theta_{12}$

Sum mass rule

$$m_1^\nu + m_2^\nu = m_3^\nu$$

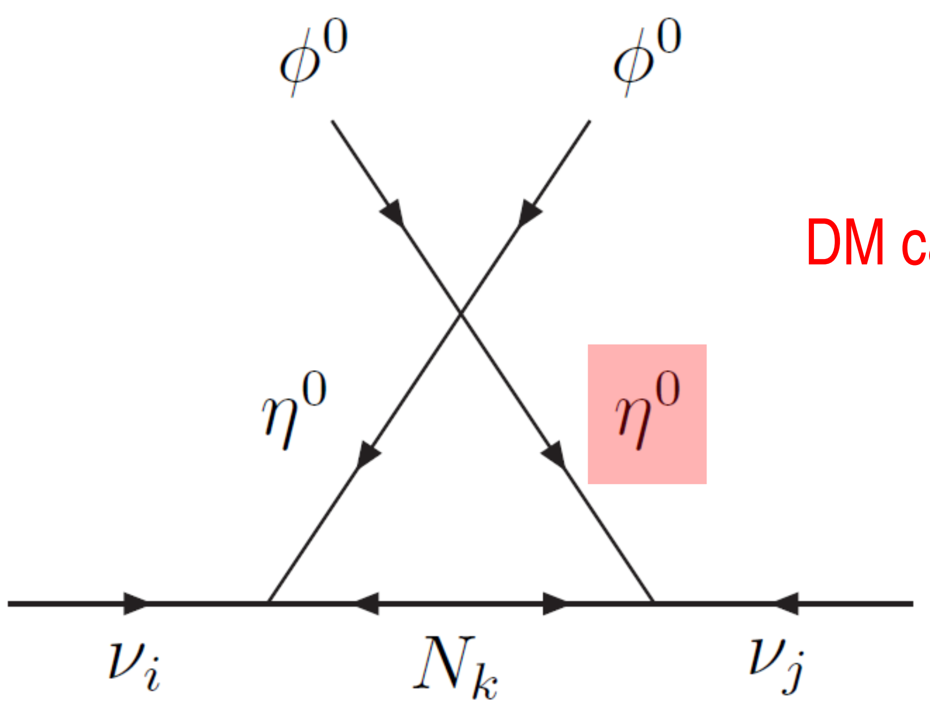
Barry, Rodejohann NPB 842 (2011)
Dorame,Meloni,M,Peinado,Valle NPB861(2011)



Outlook

Scotogenic model

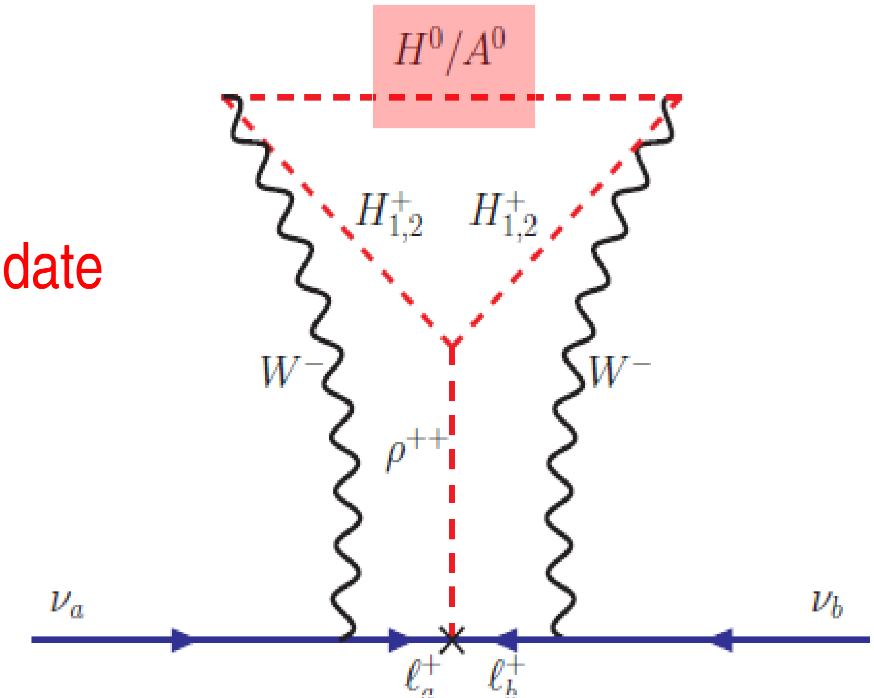
Ma, PRD73 (06')



DM candidate

Cocktail model

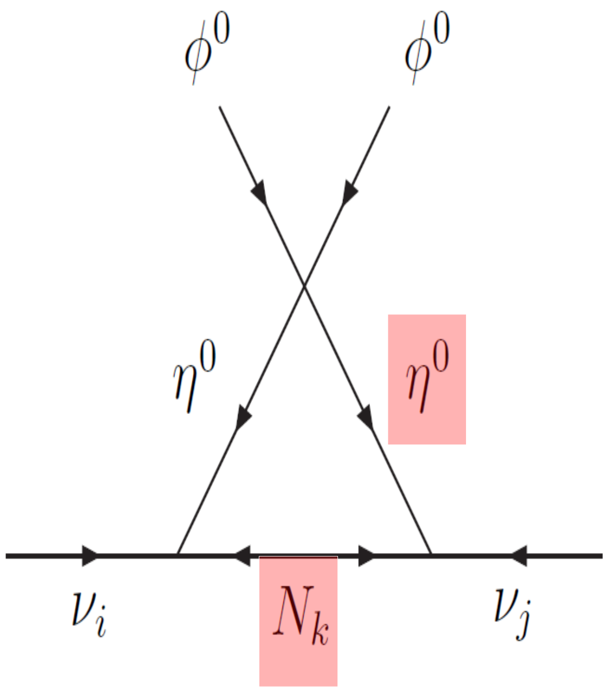
Gustafsson, No, Rivera (12')



Neutrino mass ⟷ Dark Matter

Scotogenic model

Ma, PRD73 (06')



$$\mathcal{V}(\phi,\eta) = m_\phi^2 \phi^\dagger\phi + m_\eta^2 \eta^\dagger\eta + \frac{\lambda_1}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 + \lambda_3\left(\phi^\dagger\phi\right)\left(\eta^\dagger\eta\right) + \lambda_4\left(\phi^\dagger\eta\right)\left(\eta^\dagger\phi\right) + \frac{\lambda_5}{2}\left(\phi^\dagger\eta\right)^2 + \mathrm{h.c.},$$

$$(m_\nu)_{\alpha\beta} \simeq \sum_{i=1}^{3} \frac{2\lambda_5 h_{\alpha i} h_{\beta i} \langle\phi^0\rangle^2}{(4\pi)^2 M_i} I\left(\frac{M_i^2}{M_\eta^2}\right)$$

DM $\begin{cases} \eta \\ N_i \end{cases}$

η → week connection between DM and neutrino

N_i → deeper connection between DM and neutrino

Accidental stability of DM

Lavoura,M,Valle *accepted in JHEP*

SU(2) is the ***double cover*** of SO(3)

1, *2*, 3, *4*,... *irrep*

1, 3, 5, ... *irrep*

Accidental stability of DM

Lavoura,M,Valle *accepted in JHEP*

SU(2) is the ***double cover*** of SO(3)

1, *2*, 3, *4* ,... *irrep* **1, 3, 5, ...** *irrep*

spinorial **We can call** vectorial

spinorial x *spinorial* → vectorial

vectorial x vectorial → vectorial

Accidental stability of DM

Lavoura,M,Valle *accepted in JHEP*

SU(2) is the ***double cover*** of SO(3)

1, 2, 3, 4,... *irrep* **1, 3, 5, ...** *irrep*

spinorial vectorial

We can call

– spinorial x – spinorial → + vectorial

+ vectorial x + vectorial → + vectorial

As an accidental Z_2

An example: T' double cover of A_4

vectorial spinorial

A_4

$\otimes$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{3}$	$\mathbf{2}_1$	$\mathbf{2}_2$	$\mathbf{2}_3$
$\mathbf{1}_1$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{3}$	$\mathbf{2}_1$	$\mathbf{2}_2$	$\mathbf{2}_3$
$\mathbf{1}_2$		$\mathbf{1}_3$	$\mathbf{1}_1$	$\mathbf{3}$	$\mathbf{2}_2$	$\mathbf{2}_3$	$\mathbf{2}_1$
$\mathbf{1}_3$			$\mathbf{1}_2$	$\mathbf{3}$	$\mathbf{2}_3$	$\mathbf{2}_1$	$\mathbf{2}_2$
$\mathbf{3}$				$\mathbf{3}, \mathbf{3}, \mathbf{1}_1, \mathbf{1}_2, \mathbf{1}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$
$\mathbf{2}_1$					$\mathbf{3}, \mathbf{1}_1$	$\mathbf{3}, \mathbf{1}_2$	$\mathbf{3}, \mathbf{1}_3$
$\mathbf{2}_2$						$\mathbf{3}, \mathbf{1}_3$	$\mathbf{3}, \mathbf{1}_1$
$\mathbf{2}_3$							$\mathbf{3}, \mathbf{1}_2$

An example: T'

$\otimes$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{3}$	$\mathbf{2}_1$	$\mathbf{2}_2$	$\mathbf{2}_3$
$\mathbf{1}_1$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{3}$	$\mathbf{2}_1$	$\mathbf{2}_2$	$\mathbf{2}_3$
$\mathbf{1}_2$		$\mathbf{1}_3$	$\mathbf{1}_1$	$\mathbf{3}$	$\mathbf{2}_2$	$\mathbf{2}_3$	$\mathbf{2}_1$
$\mathbf{1}_3$			$\mathbf{1}_2$	$\mathbf{3}$	$\mathbf{2}_3$	$\mathbf{2}_1$	$\mathbf{2}_2$
$\mathbf{3}$				$\mathbf{3}, \mathbf{3}, \mathbf{1}_1, \mathbf{1}_2, \mathbf{1}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$
$\mathbf{2}_1$					$\mathbf{3}, \mathbf{1}_1$	$\mathbf{3}, \mathbf{1}_2$	$\mathbf{3}, \mathbf{1}_3$
$\mathbf{2}_2$						$\mathbf{3}, \mathbf{1}_3$	$\mathbf{3}, \mathbf{1}_1$
$\mathbf{2}_3$							$\mathbf{3}, \mathbf{1}_2$

vectorial x vectorial → vectorial

An example: T'

$\otimes$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{3}$	$\mathbf{2}_1$	$\mathbf{2}_2$	$\mathbf{2}_3$
$\mathbf{1}_1$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{3}$	$\mathbf{2}_1$	$\mathbf{2}_2$	$\mathbf{2}_3$
$\mathbf{1}_2$		$\mathbf{1}_3$	$\mathbf{1}_1$	$\mathbf{3}$	$\mathbf{2}_2$	$\mathbf{2}_3$	$\mathbf{2}_1$
$\mathbf{1}_3$			$\mathbf{1}_2$	$\mathbf{3}$	$\mathbf{2}_3$	$\mathbf{2}_1$	$\mathbf{2}_2$
$\mathbf{3}$				$\mathbf{3}, \mathbf{3}, \mathbf{1}_1, \mathbf{1}_2, \mathbf{1}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$
$\mathbf{2}_1$					$\mathbf{3}, \mathbf{1}_1$	$\mathbf{3}, \mathbf{1}_2$	$\mathbf{3}, \mathbf{1}_3$
$\mathbf{2}_2$						$\mathbf{3}, \mathbf{1}_3$	$\mathbf{3}, \mathbf{1}_1$
$\mathbf{2}_3$							$\mathbf{3}, \mathbf{1}_2$

spinorial x *spinorial* → vectorial

An example: T'

$\otimes$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{3}$	$\mathbf{2}_1$	$\mathbf{2}_2$	$\mathbf{2}_3$
$\mathbf{1}_1$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{3}$	$\mathbf{2}_1$	$\mathbf{2}_2$	$\mathbf{2}_3$
$\mathbf{1}_2$		$\mathbf{1}_3$	$\mathbf{1}_1$	$\mathbf{3}$	$\mathbf{2}_2$	$\mathbf{2}_3$	$\mathbf{2}_1$
$\mathbf{1}_3$			$\mathbf{1}_2$	$\mathbf{3}$	$\mathbf{2}_3$	$\mathbf{2}_1$	$\mathbf{2}_2$
$\mathbf{3}$				$\mathbf{3}, \mathbf{3}, \mathbf{1}_1, \mathbf{1}_2, \mathbf{1}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$
$\mathbf{2}_1$					$\mathbf{3}, \mathbf{1}_1$	$\mathbf{3}, \mathbf{1}_2$	$\mathbf{3}, \mathbf{1}_3$
$\mathbf{2}_2$						$\mathbf{3}, \mathbf{1}_3$	$\mathbf{3}, \mathbf{1}_1$
$\mathbf{2}_3$							$\mathbf{3}, \mathbf{1}_2$

spinorial x vectorial → *spinorial*

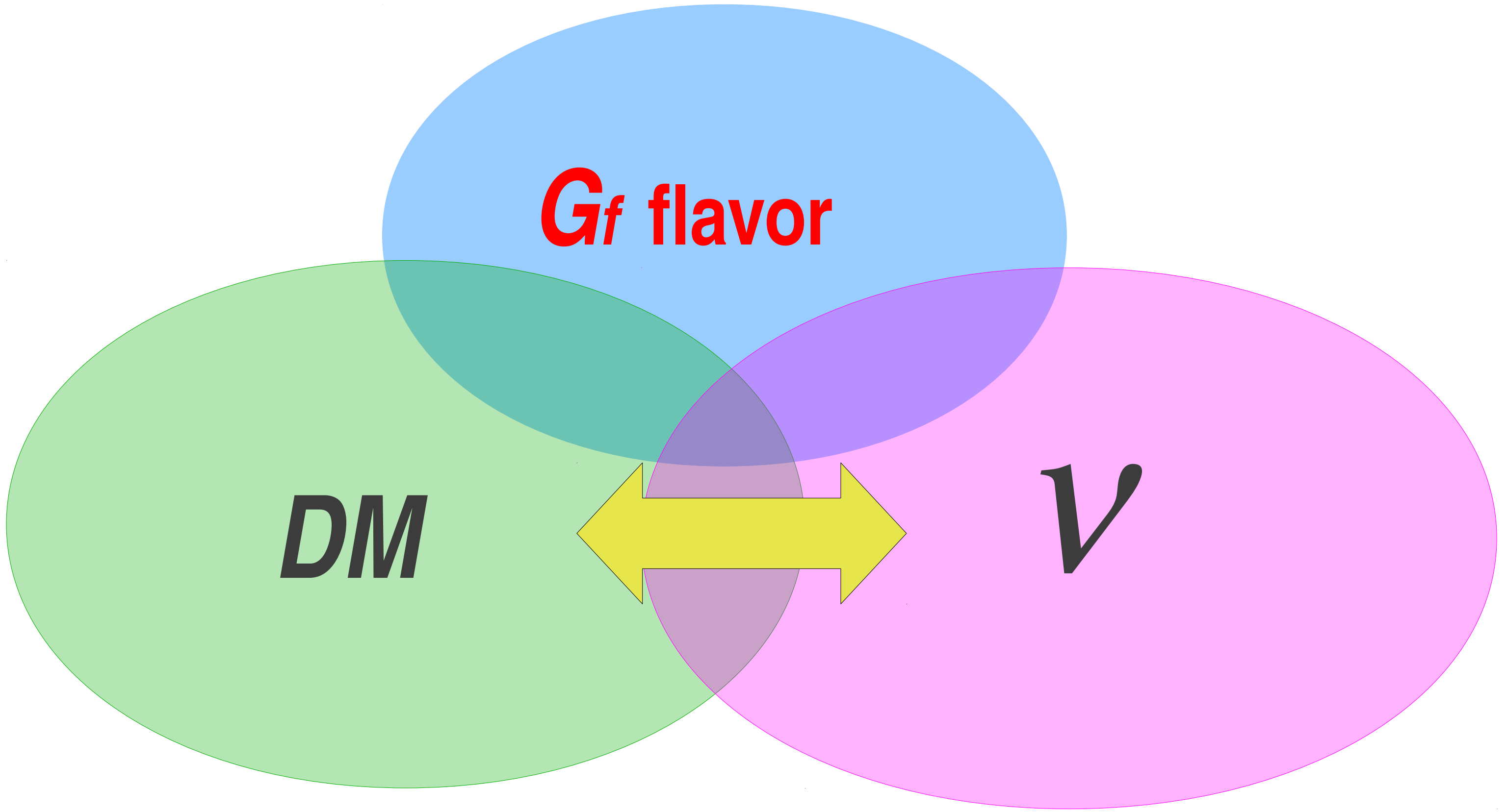
An example: T'

Your favorite A4 model **Stable DM**

$\otimes$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{3}$	$\mathbf{2}_1$	$\mathbf{2}_2$	$\mathbf{2}_3$
$\mathbf{1}_1$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	$\mathbf{3}$	$\mathbf{2}_1$	$\mathbf{2}_2$	$\mathbf{2}_3$
$\mathbf{1}_2$		$\mathbf{1}_3$	$\mathbf{1}_1$	$\mathbf{3}$	$\mathbf{2}_2$	$\mathbf{2}_3$	$\mathbf{2}_1$
$\mathbf{1}_3$			$\mathbf{1}_2$	$\mathbf{3}$	$\mathbf{2}_3$	$\mathbf{2}_1$	$\mathbf{2}_2$
$\mathbf{3}$				$\mathbf{3}, \mathbf{3}, \mathbf{1}_1, \mathbf{1}_2, \mathbf{1}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$	$\mathbf{2}_1, \mathbf{2}_2, \mathbf{2}_3$
$\mathbf{2}_1$					$\mathbf{3}, \mathbf{1}_1$	$\mathbf{3}, \mathbf{1}_2$	$\mathbf{3}, \mathbf{1}_3$
$\mathbf{2}_2$						$\mathbf{3}, \mathbf{1}_3$	$\mathbf{3}, \mathbf{1}_1$
$\mathbf{2}_3$							$\mathbf{3}, \mathbf{1}_2$

Conclusions

DM stability from flavor symmetry



Backup slides

Neutrino in discrete DM model

	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

$$
\begin{aligned}
\mathcal{L} \;=\; & y_e L_e l_e^c \hat{H} + y_\mu L_\mu l_\mu^c \hat{H} + y_\tau L_\tau l_\tau^c \hat{H} + \\
& + y_1^\nu L_e (N_T \eta)_1 + y_2^\nu L_\mu (N_T \eta)_{1''} + y_3^\nu L_\tau (N_T \eta)_{1'} + \\
& + y_4^\nu L_e N_4 \hat{H} + M_1 N_T N_T + M_2 N_4 N_4 + \text{h.c.}
\end{aligned}
$$

$$
m_D = \begin{pmatrix} x_1 & 0 & 0 & x_4 \\ x_2 & 0 & 0 & 0 \\ x_3 & 0 & 0 & 0 \end{pmatrix}, \quad
M_R = \begin{pmatrix} M_1 & 0 & 0 & 0 \\ 0 & M_1 & 0 & 0 \\ 0 & 0 & M_1 & 0 \\ 0 & 0 & 0 & M_2 \end{pmatrix}
$$

$$
m_\nu = -m_{D_{3\times 4}} M^{-1}_{R_{4\times 4}} m^T_{D_{3\times 4}} \equiv \begin{pmatrix} y^2 & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{pmatrix}
$$

D(54) isomorphic to → $(Z_3 \times Z_3) \rtimes S_3$

N=3

$\Delta(6N^2)$

$$a^N = a'^N = b^3 = c^2 = (bc)^2 = e,$$
$$aa' = a'a,$$
$$bab^{-1} = a^{-1}a'^{-1}, \qquad ba'b^{-1} = a,$$
$$cac^{-1} = a'^{-1}, \qquad ca'c^{-1} = a^{-1}.$$

Ishimori et al., Prog.Theor.Phys.Suppl. 183

	$\overline{L}_e$	$\overline{L}_D$	e_R	l_D	H	χ	η	Δ
$SU(2)$	2	2	1	1	2	2	2	3
$\Delta(54)$	$\mathbf{1}_+$	$\mathbf{2}_1$	$\mathbf{1}_+$	$\mathbf{2}_1$	$\mathbf{1}_+$	$\mathbf{2}_1$	$\mathbf{2}_3$	$\mathbf{2}_1$

	$Q_{1,2}$	Q_3	(u_R, c_R)	t_R	d_R	s_R	b_R
$SU(2)$	2	2	1	1	1	1	1
$\Delta(54)$	$\mathbf{2}_1$	$\mathbf{1}_+$	$\mathbf{2}_1$	$\mathbf{1}_+$	$\mathbf{1}_-$	$\mathbf{1}_+$	$\mathbf{1}_+$

We assume real parameters

$$M_\ell = \begin{pmatrix} a & br & b \\ cr & d & e \\ c & e & dr \end{pmatrix}$$

$$M_d = \begin{pmatrix} ra_d & rb_d & rd_d \\ -a_d & b_d & d_d \\ 0 & c_d & e_d \end{pmatrix}$$

r common to the two sectors

$$0.1 < r < 0.2$$

$$M_\nu \propto \begin{pmatrix} 0 & \delta & \delta \\ \delta & \alpha & 0 \\ \delta & 0 & \alpha \end{pmatrix}$$

$$M_u = \begin{pmatrix} ra_u & b_u & d_u \\ b_u & a_u & rd_u \\ c_u & rc_u & e_u \end{pmatrix}$$

8 parameters

10 parameters

Accidental stability of DM

-		-		+	
spinorial	x	*spinorial*	→	vectorial	As an accidental
+		+		+	
vectorial	x	vectorial	→	vectorial	Z_2

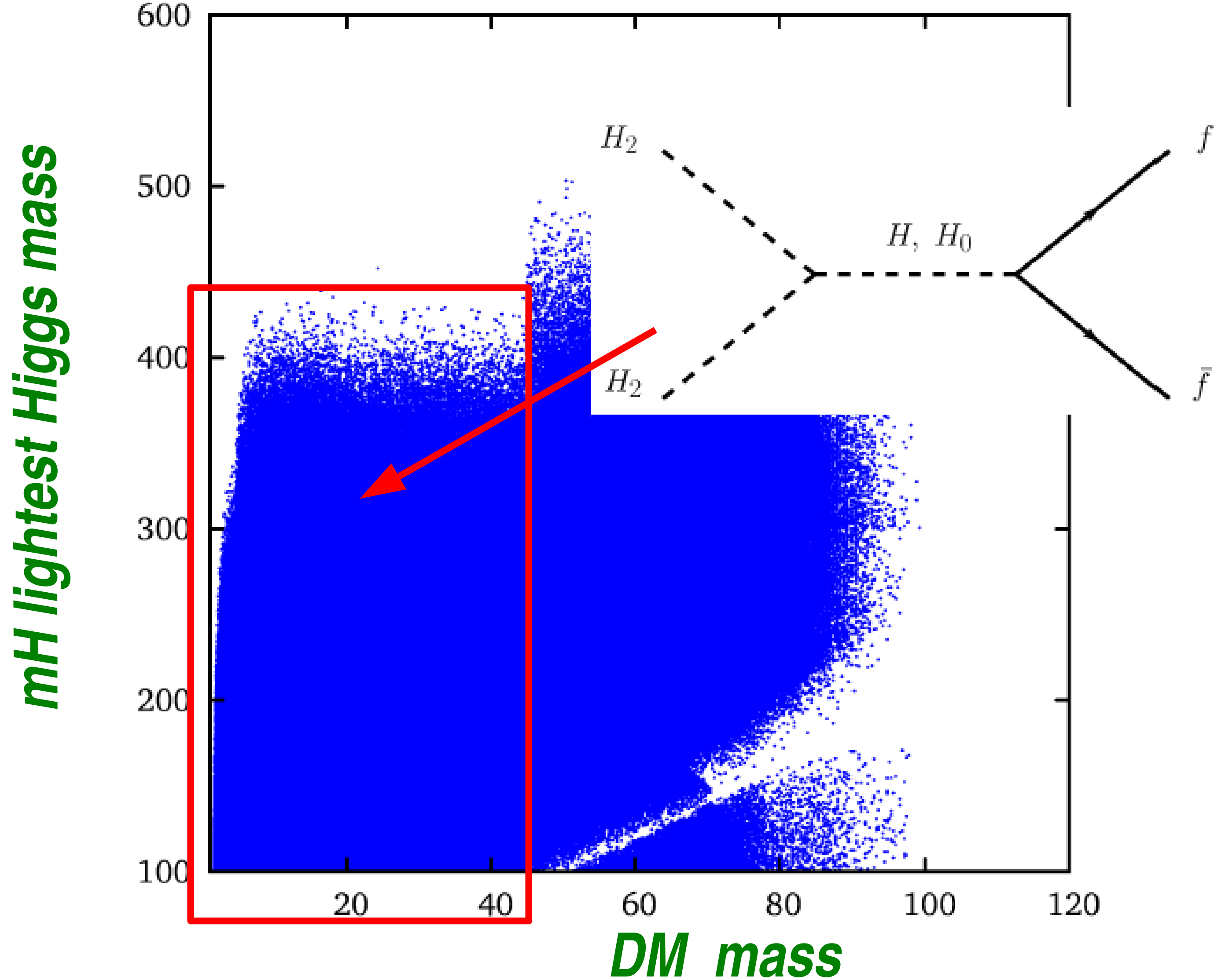
$\eta\eta$ $\eta\eta\eta\eta$ $\eta\eta H H$

$\langle\eta\rangle_0 = 0$ No terms linear in η

Relic density

$$0.09 \leq \Omega h^2 \leq 0.13$$

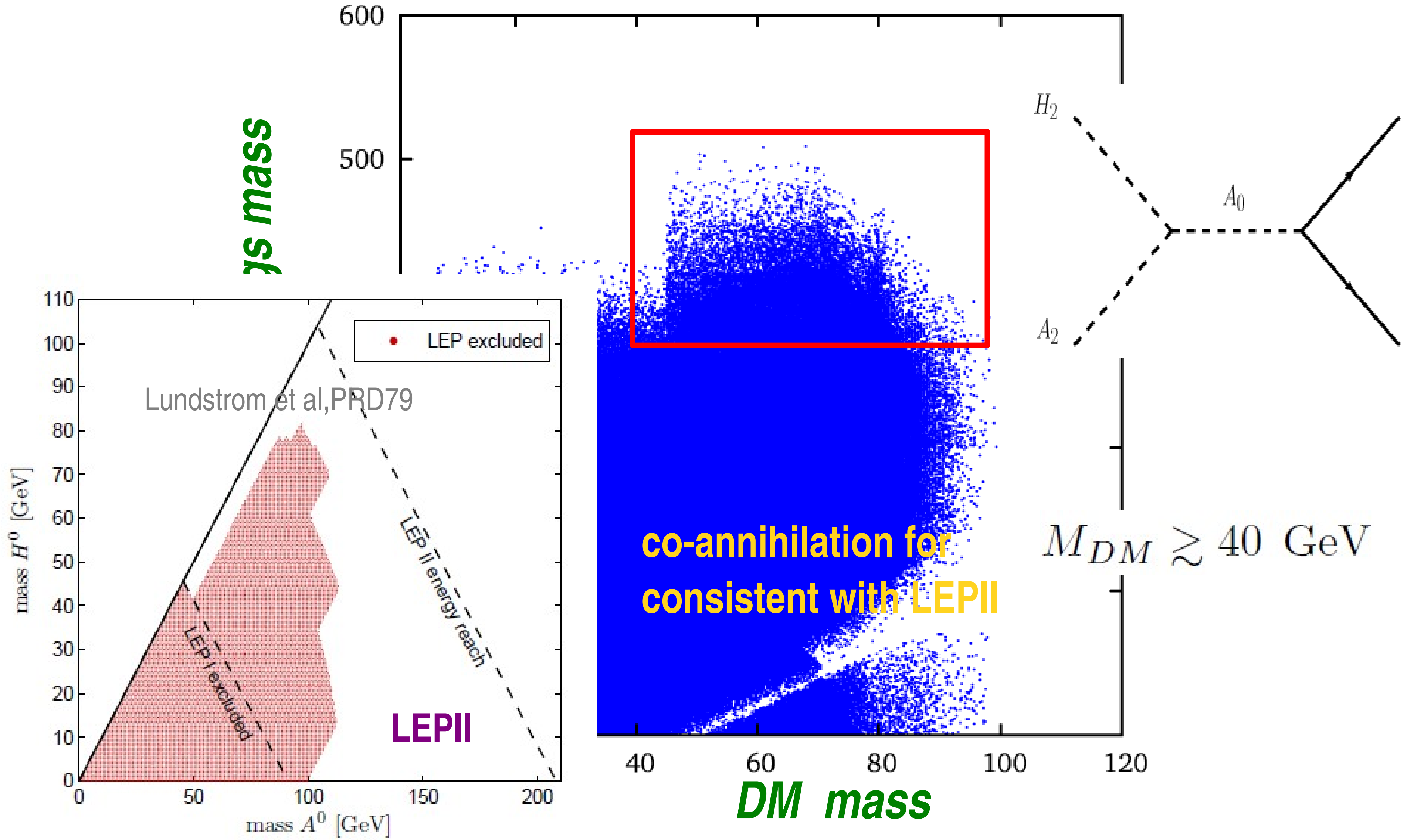
Boucenna *et al.*, ***JHEP1105 (2011)***



Relic density

$$0.09 \leq \Omega h^2 \leq 0.13$$

Boucenna *et al.*, ***JHEP1105 (2011)***

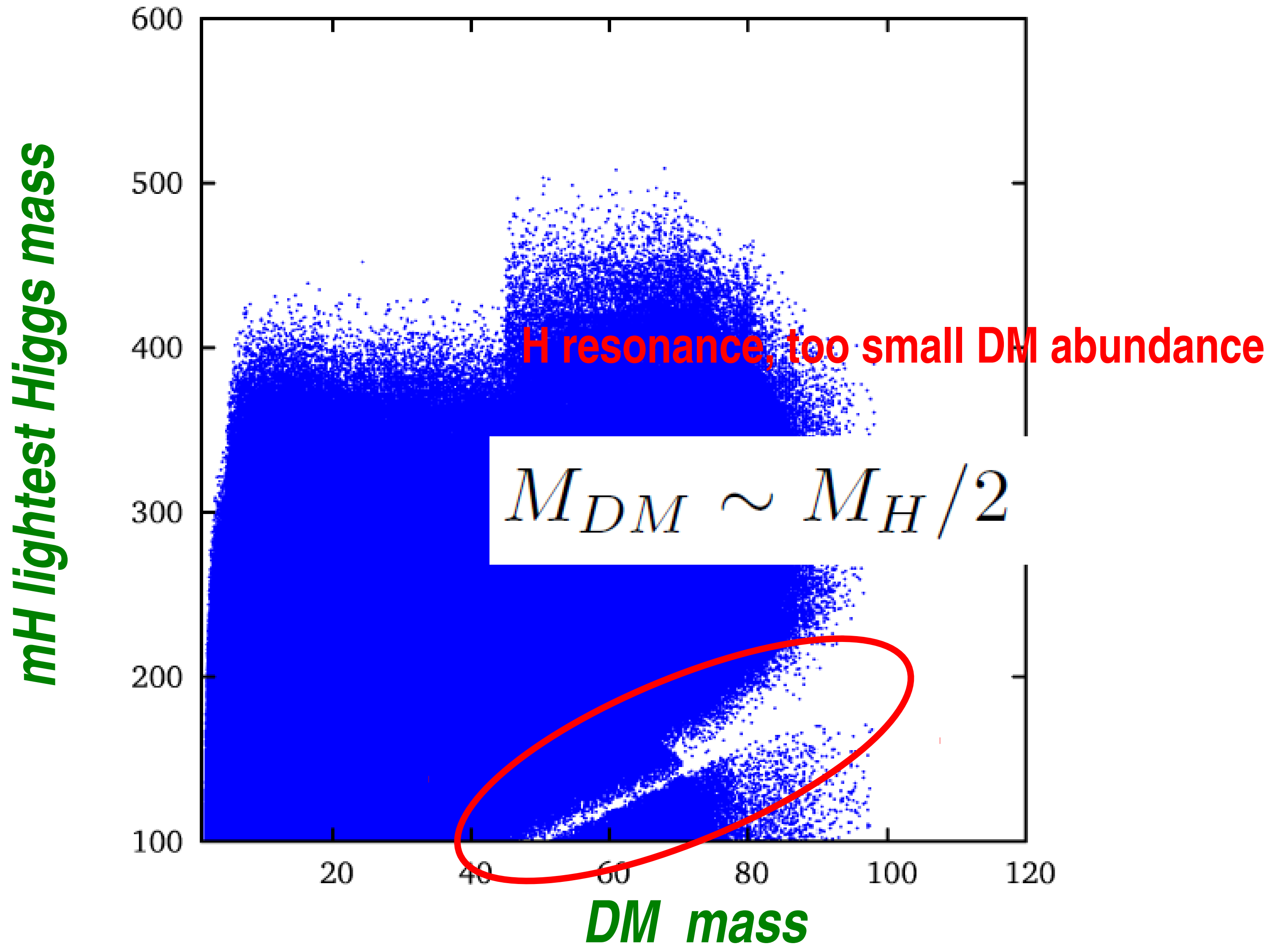


$$M_{DM} \gtrsim 40 \text{ GeV}$$

Relic density

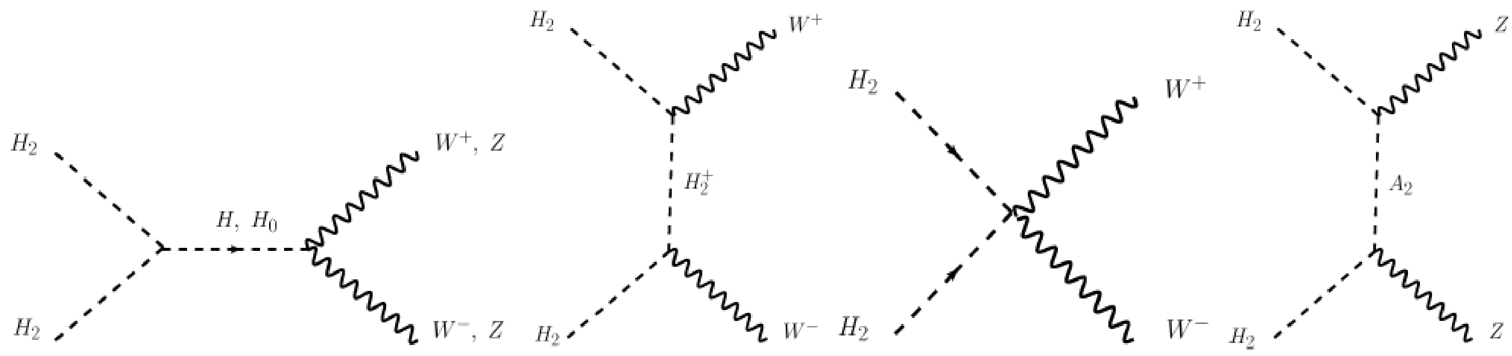
$$0.09 \leq \Omega h^2 \leq 0.13$$

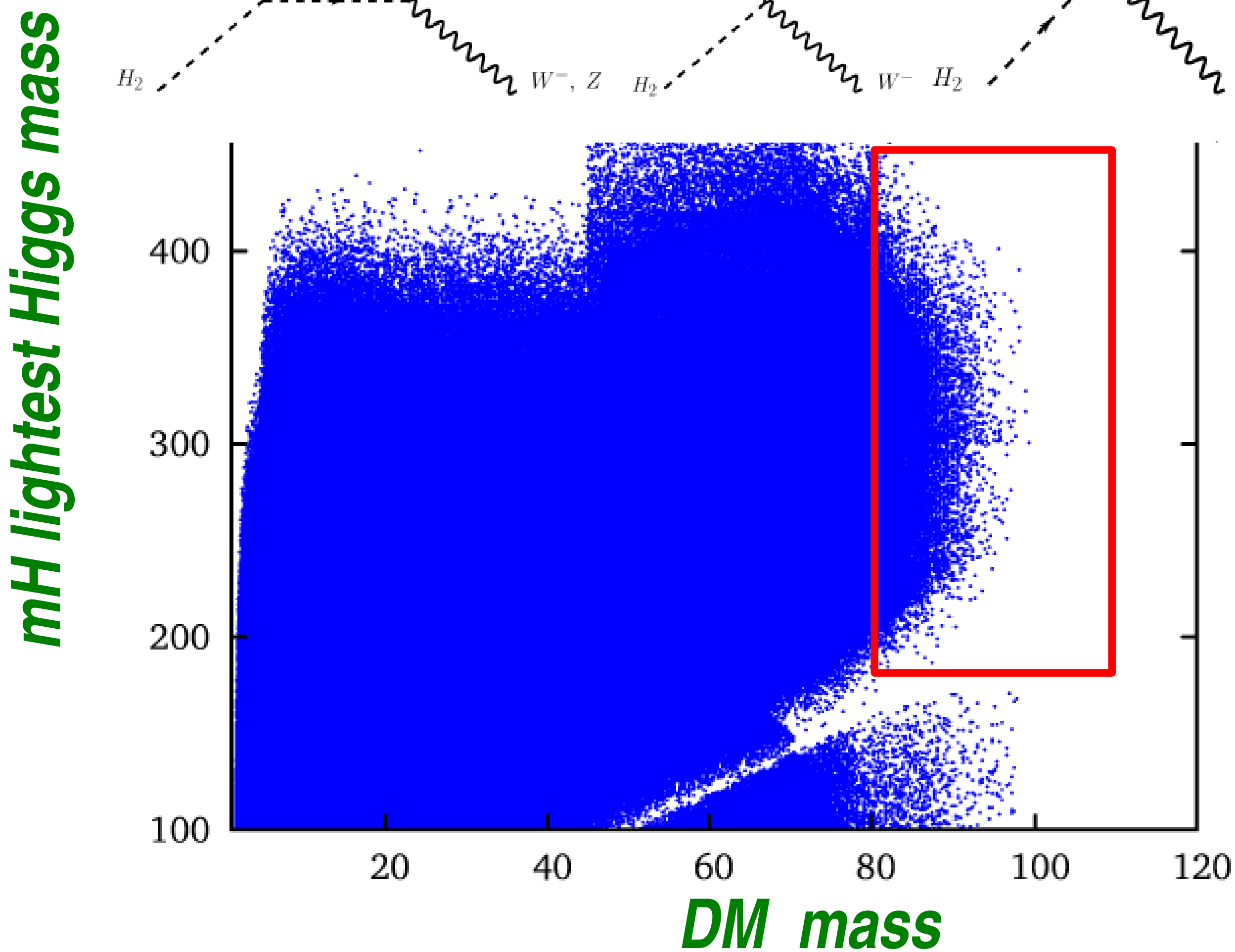
Boucenna *et al.*, ***JHEP1105 (2011)***



Relic density

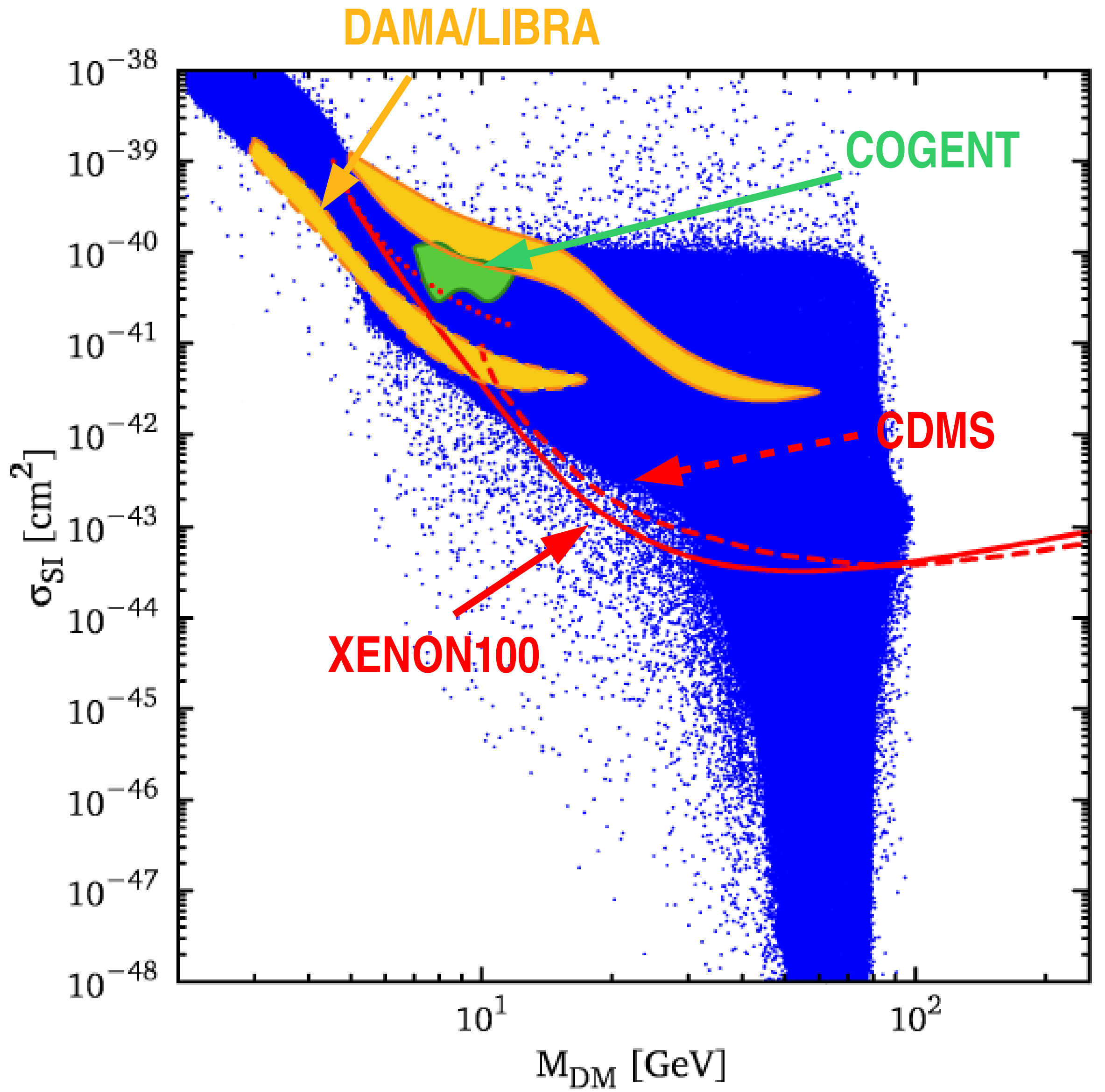
$$0.09 \leq \Omega h^2 \leq 0.13$$





Direct detection

Boucenna *et al.*, ***JHEP1105 (2011)***



Quarks

Adelhart,Bazzocchi,Morisi *1104.5676*

$$\sum \frac{f_{ij}}{\Lambda^2}(\overline{Q}_i \hat{H}) d_j (\eta^\dagger \eta) + \frac{f'_{ij}}{\Lambda^2}(\overline{Q}_i \eta) d_j (\eta^\dagger \hat{H}) + \frac{f''_{ij}}{\Lambda^2}(\overline{Q}_i \eta) d_j (\hat{H}^\dagger \eta)$$

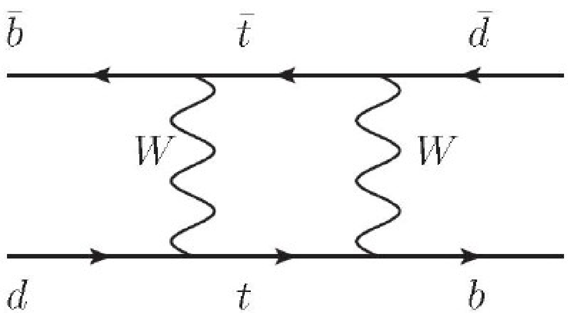
$$M_d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} + \frac{v_H v_\eta^2}{\Lambda^2} \begin{pmatrix} h_{dd} & h_{ds} & h_{db} \\ h_{sd} & h_{ss} & h_{sb} \\ h_{bd} & h_{bs} & h_{bb} \end{pmatrix} + \mathcal{O}(1/\Lambda^4)\,,$$

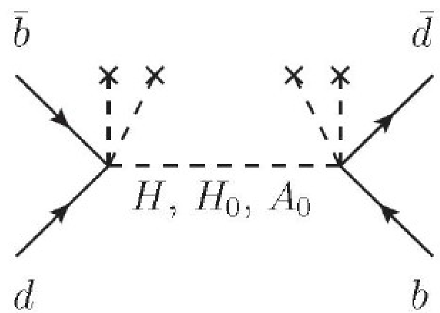
$$h_{ds} \frac{v_H v_\eta^2}{\Lambda^2} = \lambda_C m_s$$

1-10 TeV

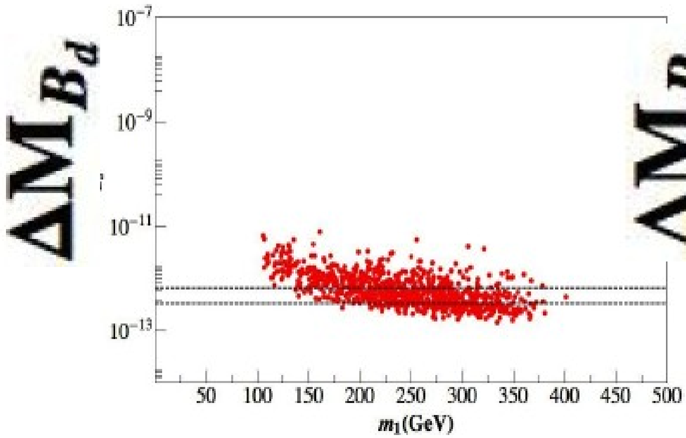
Quarks: FCNC

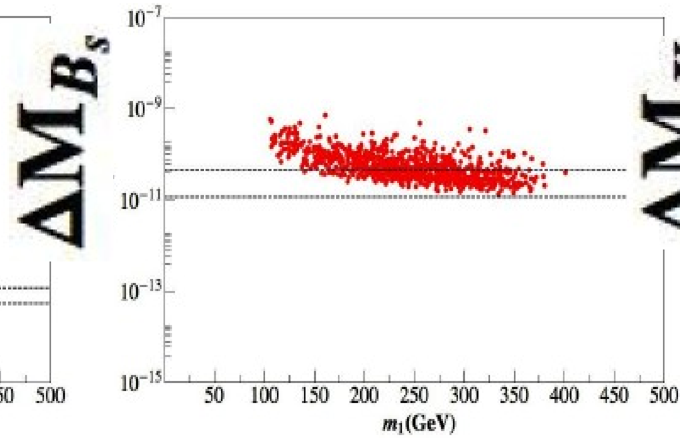
Adelhart,Bazzocchi,Morisi *1104.5676*

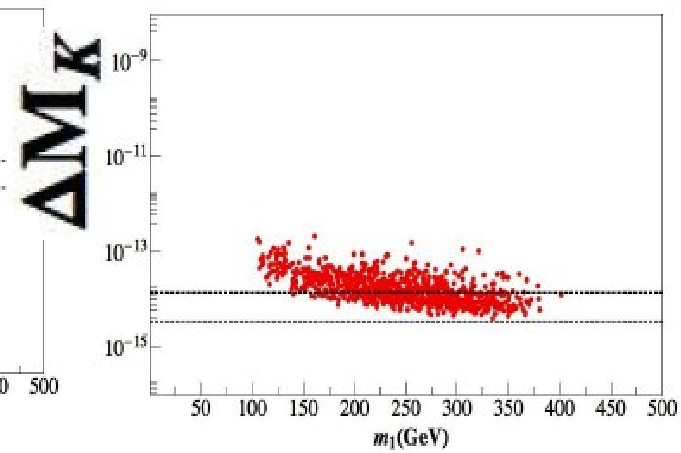




CKM mostly from down sector







lightest Higgs mass

Outlook for DDM: embedding into GUT

	T_1	T_2	T_3	F_1	F_2	F_3	N_T	N_4
SU(5)	10	10	10	$\bar{5}$	$\bar{5}$	$\bar{5}$	1	1
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1

matter

SU(5)	5_H	$\bar{5}_H$	5_η	45_H
A_4	1	1	3	1

scalar

$$\begin{aligned}
\mathcal{L}_{down} &= y_1^{l,d} T_1 F_1 \bar{5}_H + y_2^{l,d} T_2 F_2 \bar{5}_H + y_3^{l,d} T_3 F_3 \bar{5}_H \quad + y_1'^{l,d} T_1 F_1 45_H + y_2'^{l,d} T_2 F_2 45_H + y_3'^{l,d} T_3 F_3 45_H; \\
\mathcal{L}_{up} &= y_1^u T_1 T_1 5_H + y_2^u T_2 T_3 5_H + y_1'^u T_1 T_1 45_H + y_2'^u T_2 T_3 45_H; \\
\mathcal{L}_\nu &= y_1^\nu T_1 N_4 5_H + y_2^\nu T_2 N_4 5_H + y_3^\nu T_3 N_4 5_H + y_1^\nu T_1 N_T 5_\eta + M_1 N_T N_T + M_2 N_4 N_4.
\end{aligned}$$

it is possible to fit the masses

$$m_e = y_1^{l,d}\langle 5_H\rangle - 3y_1'^{l,d}\langle 45_H\rangle; \;\; m_\mu = y_2^{l,d}\langle 5_H\rangle - 3y_2'^{l,d}\langle 45_H\rangle; \;\; m_\tau = y_3^{l,d}\langle 5_H\rangle - 3y_3'^{l,d}\langle 45_H\rangle;$$

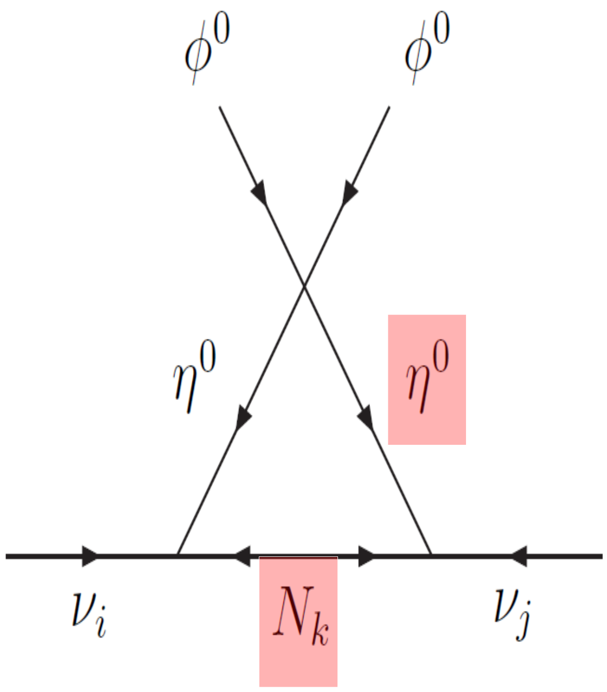
$$m_d = y_1^{l,d}\langle 5_H\rangle + y_1'^{l,d}\langle 45_H\rangle; \quad m_s = y_2^{l,d}\langle 5_H\rangle + y_2'^{l,d}\langle 45_H\rangle; \quad m_b = y_3^{l,d}\langle 5_H\rangle + y_3'^{l,d}\langle 45_H\rangle;$$

$$m_u = y_1^u\langle 5_H\rangle; \qquad m_c = y_2^u\langle 5_H\rangle - y_2'^u\langle 45_H\rangle; \qquad m_t = y_2^u\langle 5_H\rangle + y_2'^u\langle 45_H\rangle.$$

CKM?

Scotogenic model

Ma, PRD73 (06')



$$\mathcal{V}(\phi,\eta) = m_\phi^2 \phi^\dagger \phi + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 + \lambda_3\left(\phi^\dagger\phi\right)\left(\eta^\dagger\eta\right) + \lambda_4\left(\phi^\dagger\eta\right)\left(\eta^\dagger\phi\right) + \frac{\lambda_5}{2}\left(\phi^\dagger\eta\right)^2 + \text{h.c.},$$

$$(m_\nu)_{\alpha\beta} \simeq \sum_{i=1}^{3} \frac{2\lambda_5 h_{\alpha i} h_{\beta i} \langle\phi^0\rangle^2}{(4\pi)^2 M_i} I\left(\frac{M_i^2}{M_\eta^2}\right)$$

DM $\begin{cases} \eta \\ N_i \end{cases}$

η → week connection between DM and neutrino

N_i → deeper connection between DM and neutrino

λ_5 overall factor, relic density function of ***h***

See for instance Schmidt, Schwetz,Toma PRD85