Flavoured Dark Matter

Eduardo Peinado

INFN – Laboratori Nazionali di Frascati

Collaborators: Boucena, Hirsch, Meloni, Morisi, Taoso, Valle

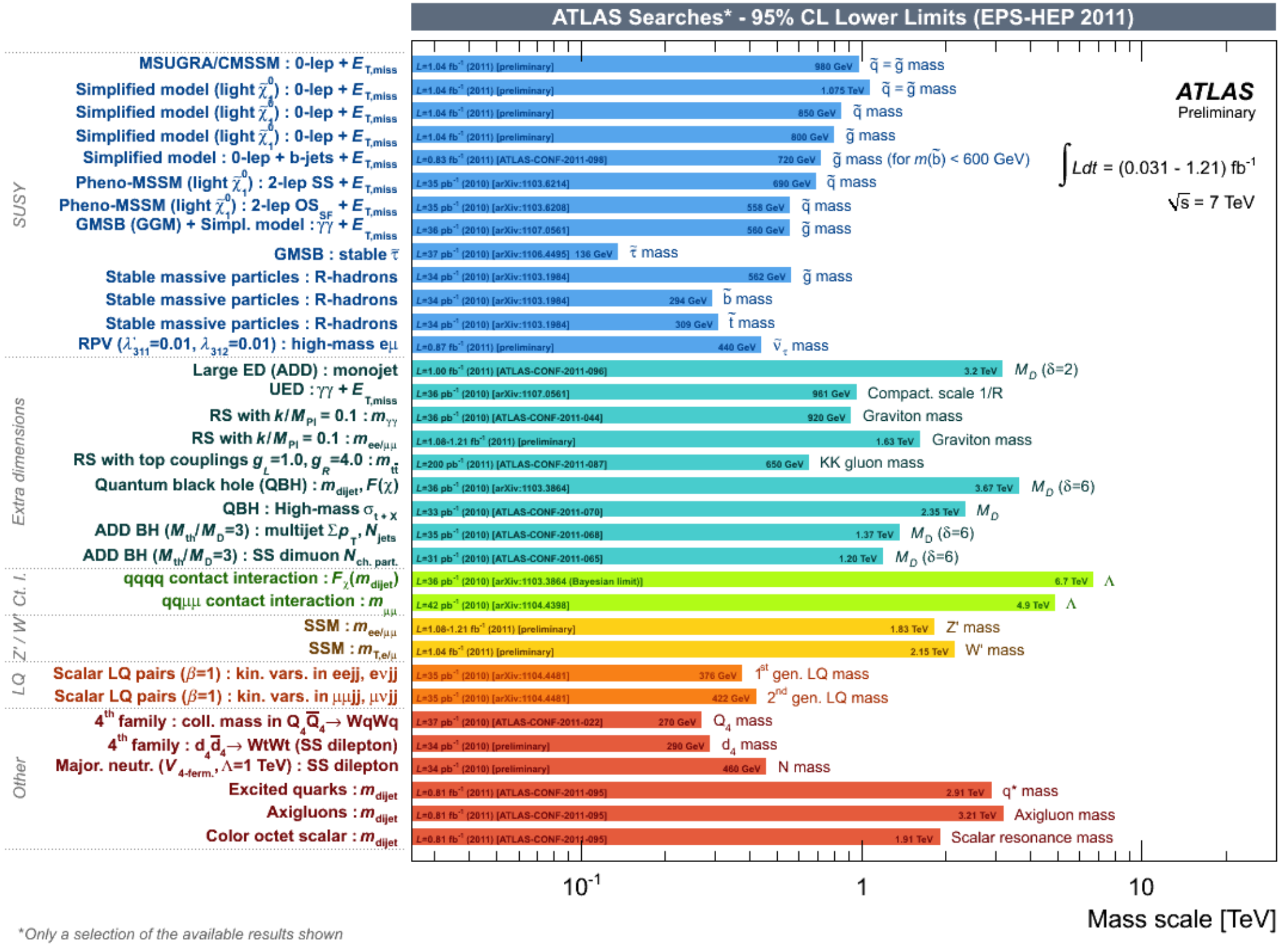
Flasy 2014
Brighton, June 2014

Plan of the talk

1) Introduction and motivations

2) Connection of DM stability and neutrinos

4) Summary and conclusions

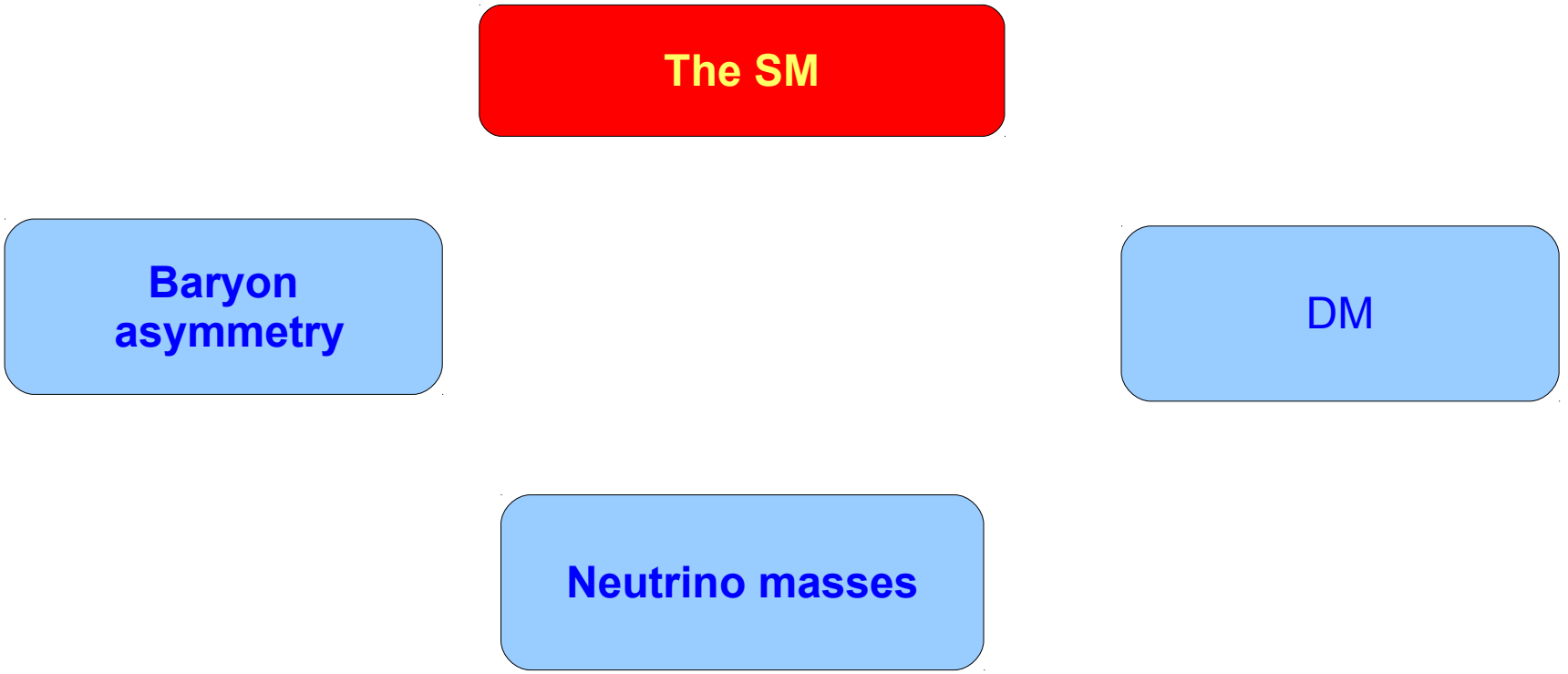


*Only a selection of the available results shown

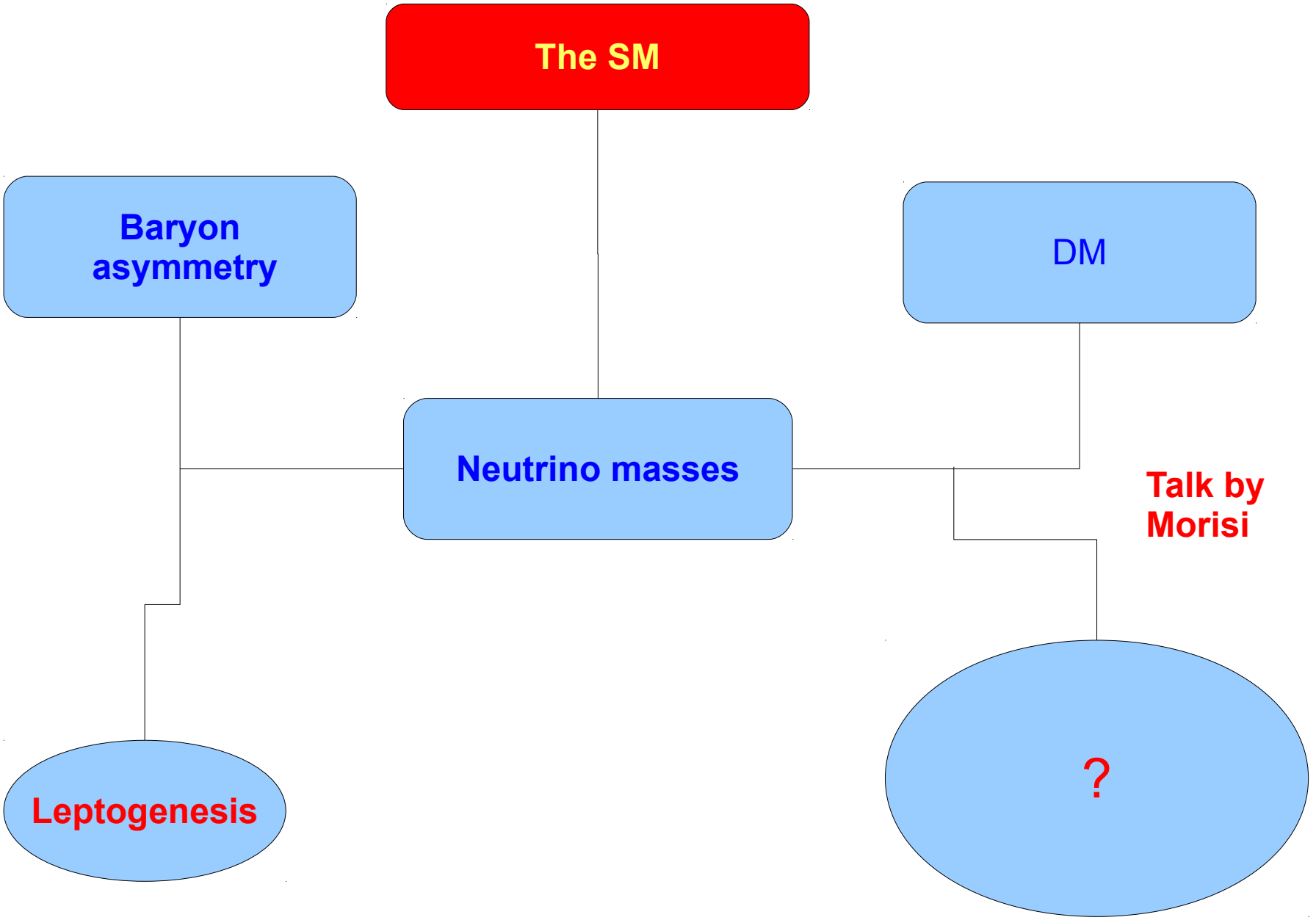
The SM

The SM

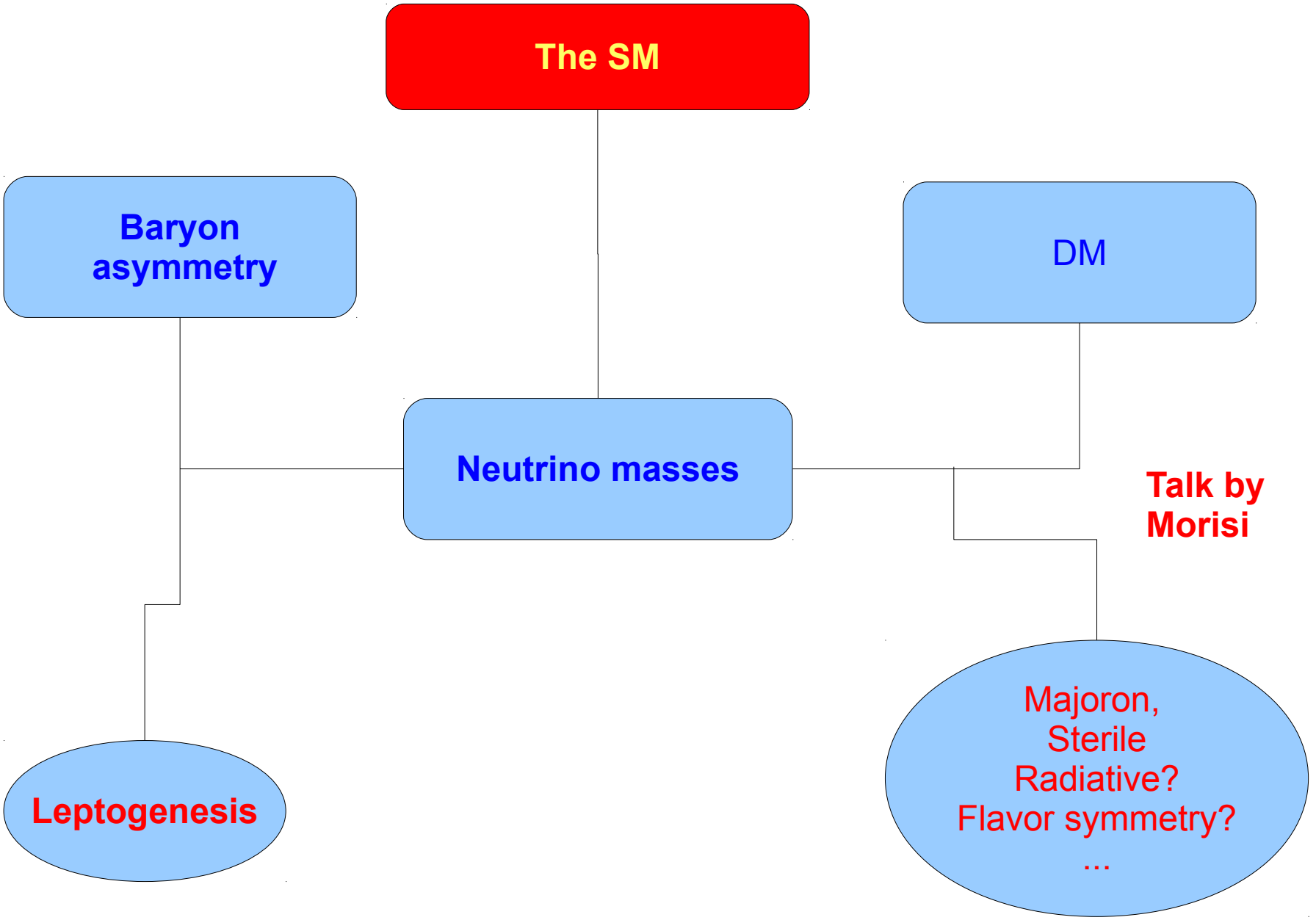
The SM



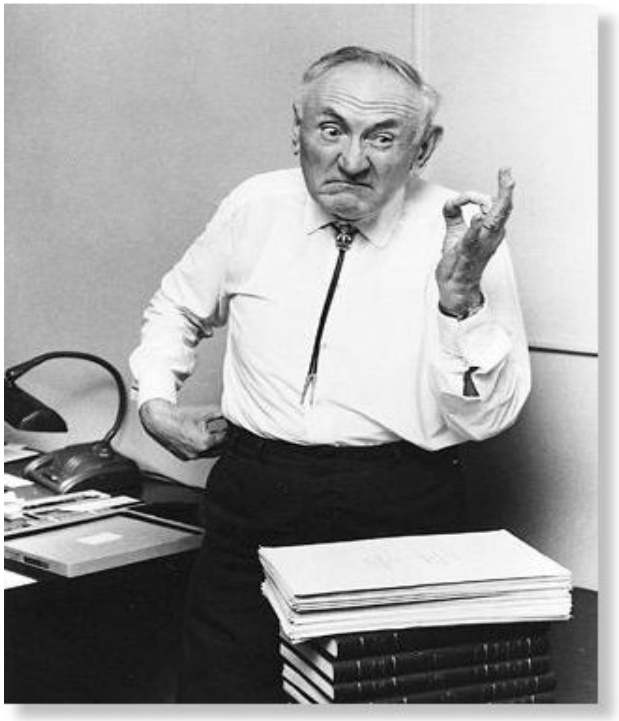
The SM

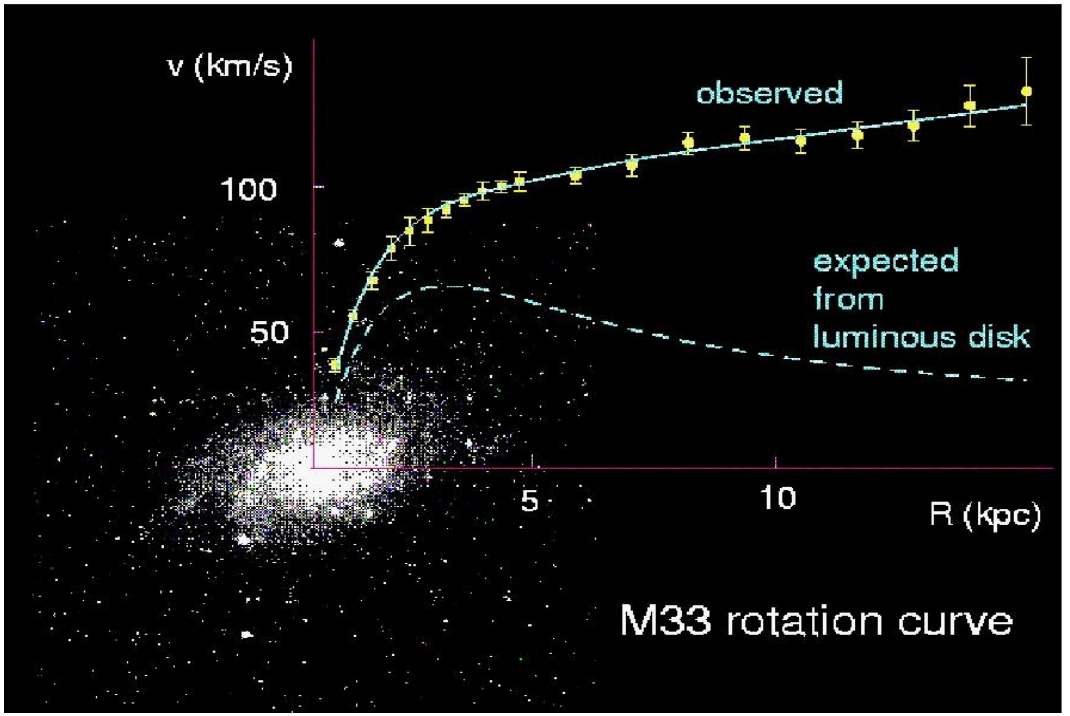

The SM
Baryon asymmetry
DM
Neutrino masses
Talk by Morisi
Leptogenesis
?

The SM


The SM
Baryon asymmetry
DM
Neutrino masses
Talk by Morisi
Leptogenesis
Majoron,
Sterile
Radiative?
Flavor symmetry?
...

Dark Matter Introduction



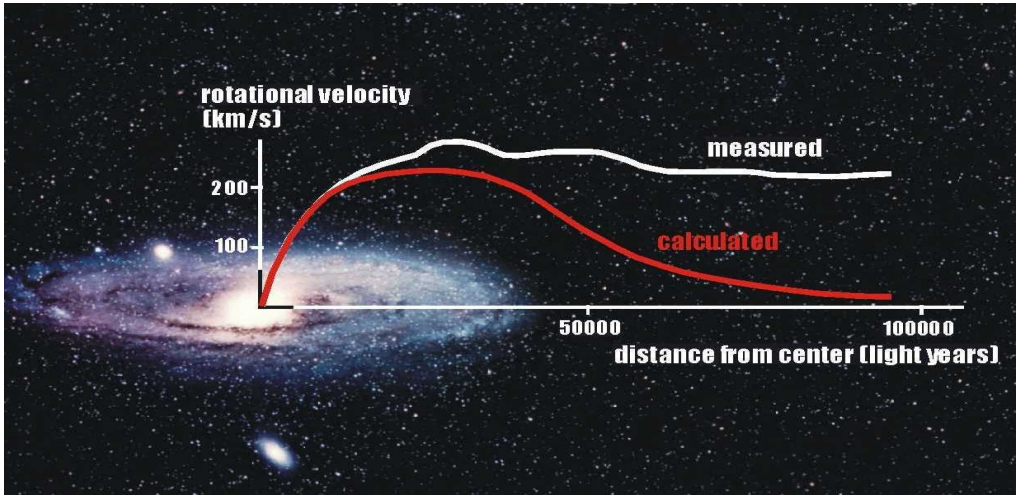


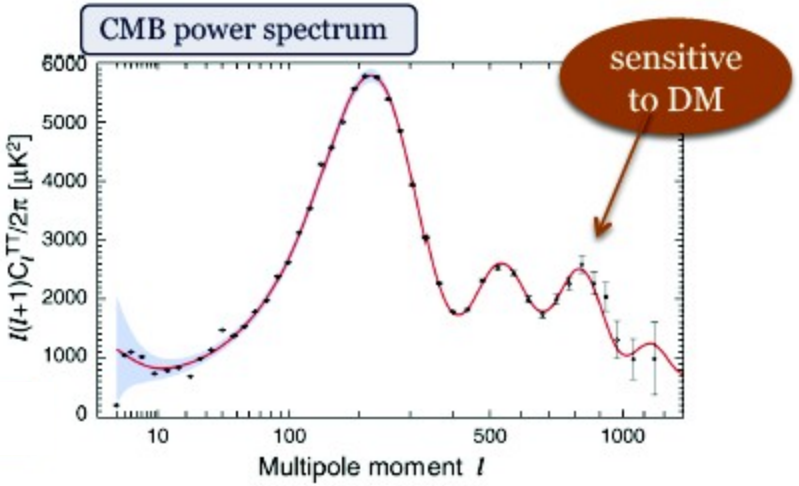
1933 Zwicky

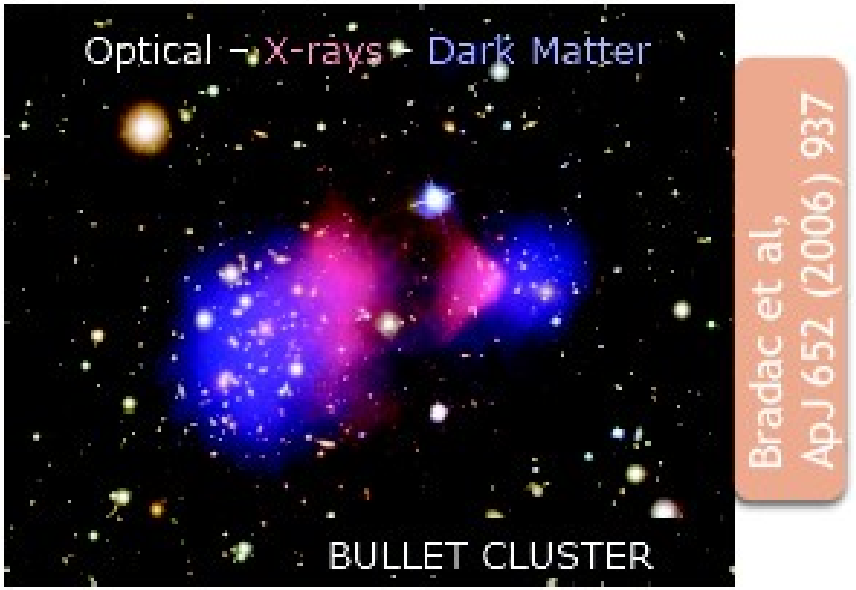
80 years

Dark Matter evidences

- Rotational curves
- Clusters of galaxies
- CMB anisotropies
- BBN
- …

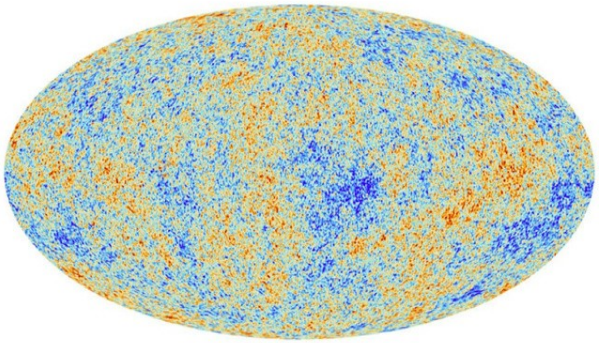


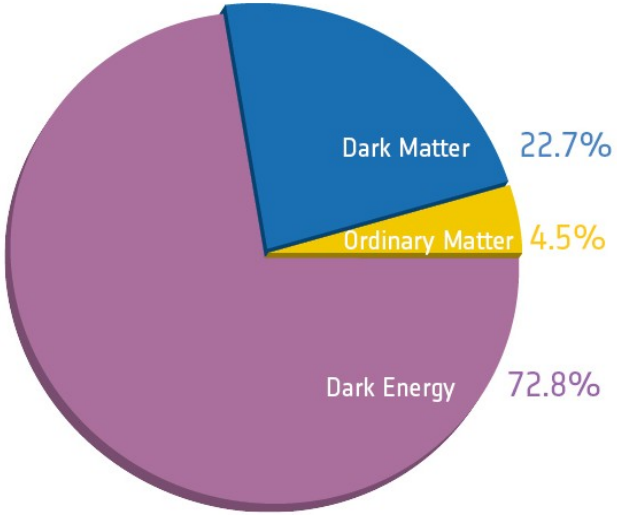




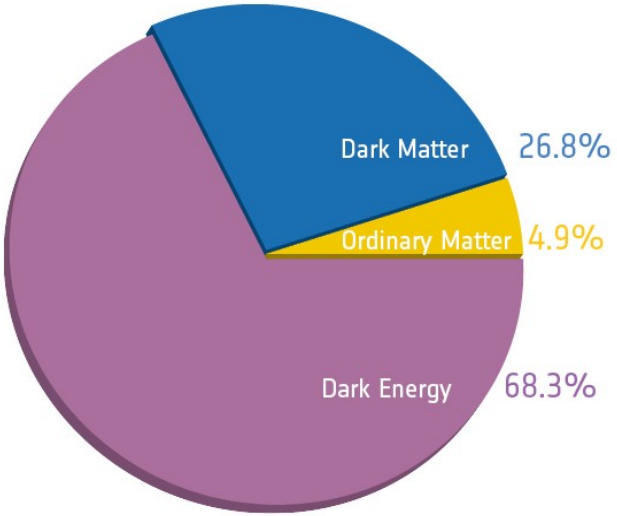
Dark Matter evidences

- Many indirect evidences of DM
- Constraint the properties of DM
- Only gravitational up to now





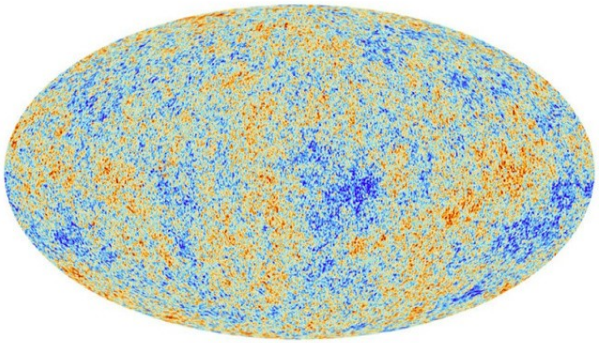
Before Planck

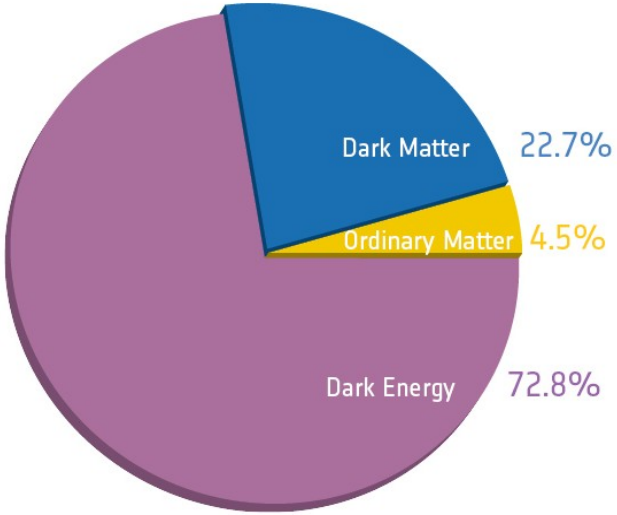


After Planck

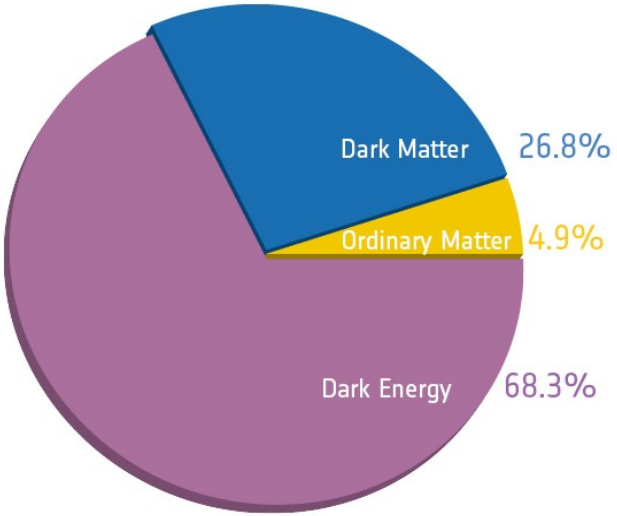
Dark Matter evidences

- Many indirect evidences of DM
- Constraint the properties of DM
- Only gravitational up to now





Before Planck



After Planck

~ 0.4 % more ordinary matter :)

What do we know?

- Long lived

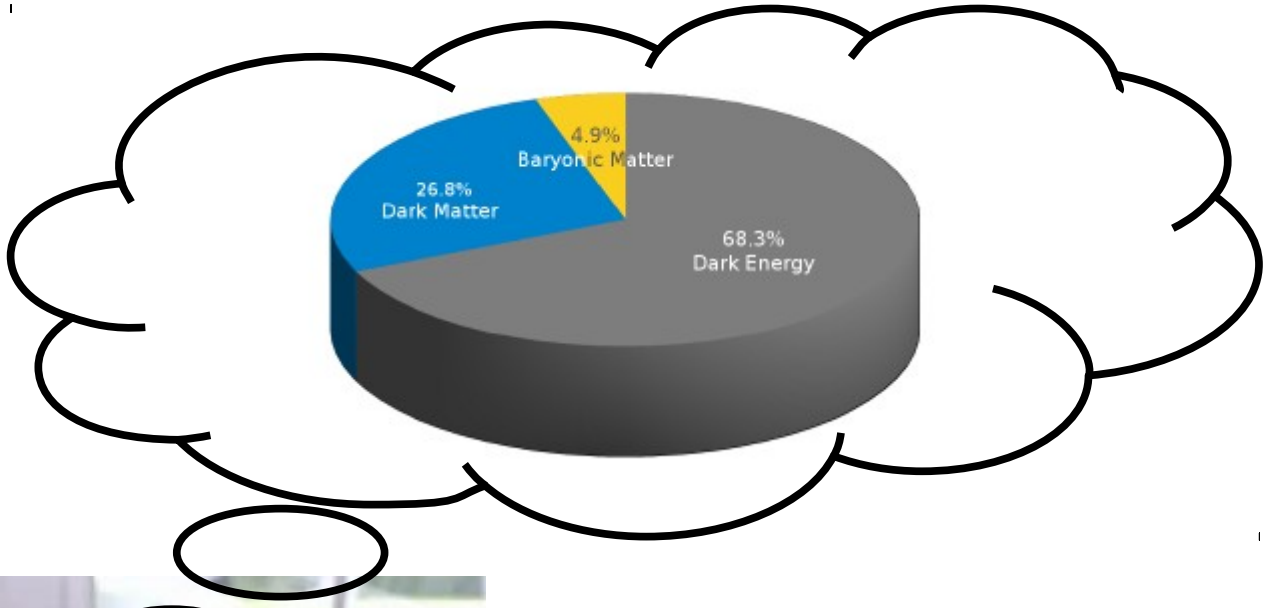
What do we know?

- Long lived (Stable)
- DM cosmological aboundance extracted from observations

What do we know?

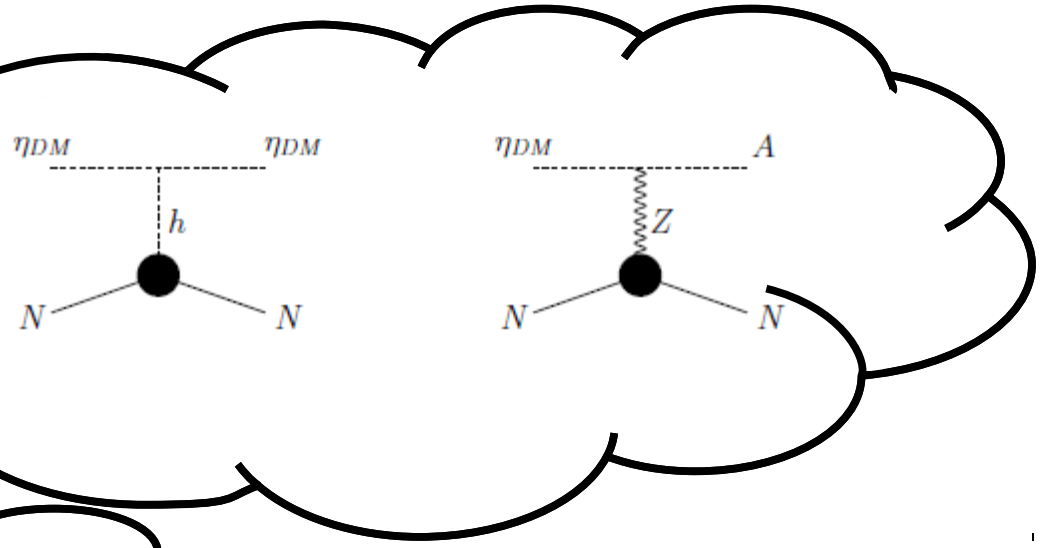
- Long lived (Stable)
- DM cosmological abundance extracted from observations
- DM is cold (or warm)
- Electrically neutral
- DM-DM and DM-SM interactions constrained by observations

Dark matter puzzle



Can we test it directly?

Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu}\widetilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i\mu\nu}\widetilde{G}^{i\mu\nu}, \frac{\partial^\mu a}{f_a}\overline{\psi}\gamma$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$



Scalar DM

SM + scalar

Talk by Pyungwon Ko

Z_2 + -

$$\lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

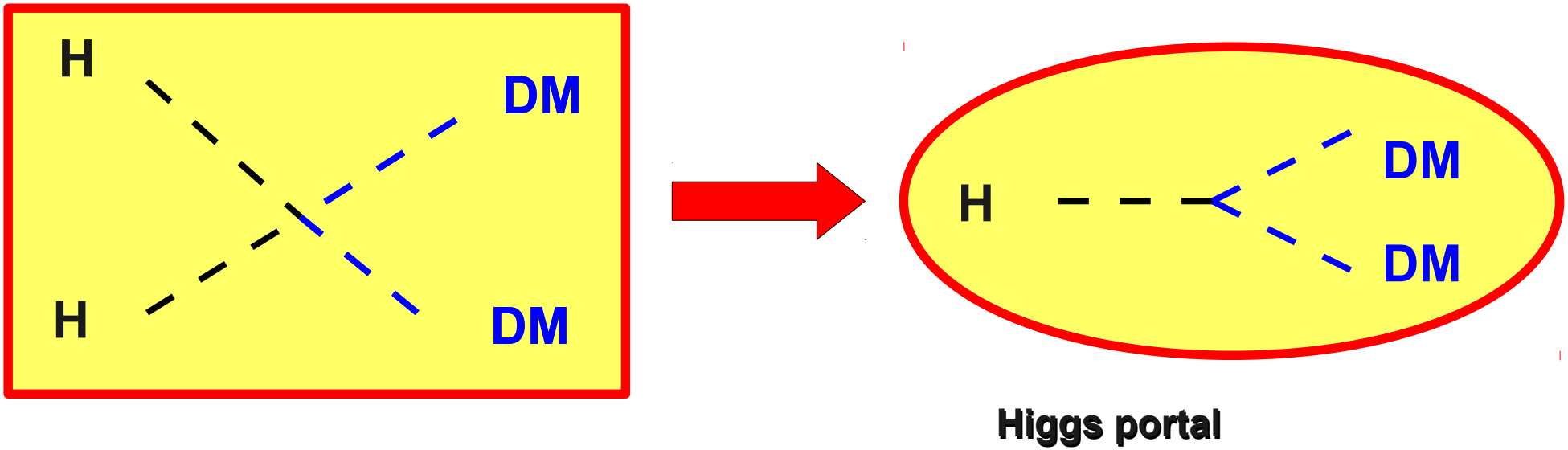
Scalar DM

SM + scalar

Talk by
Pyungwon Ko

Z_2 + -

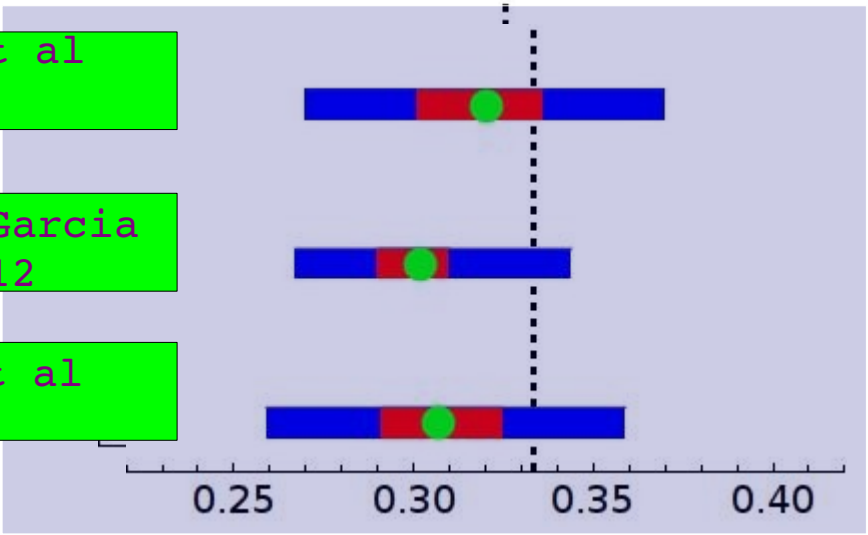
$$\lambda_3|H_1|^2|H_2|^2+\lambda_4|H_1^\dagger H_2|^2+\frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2+h.c.\right]$$

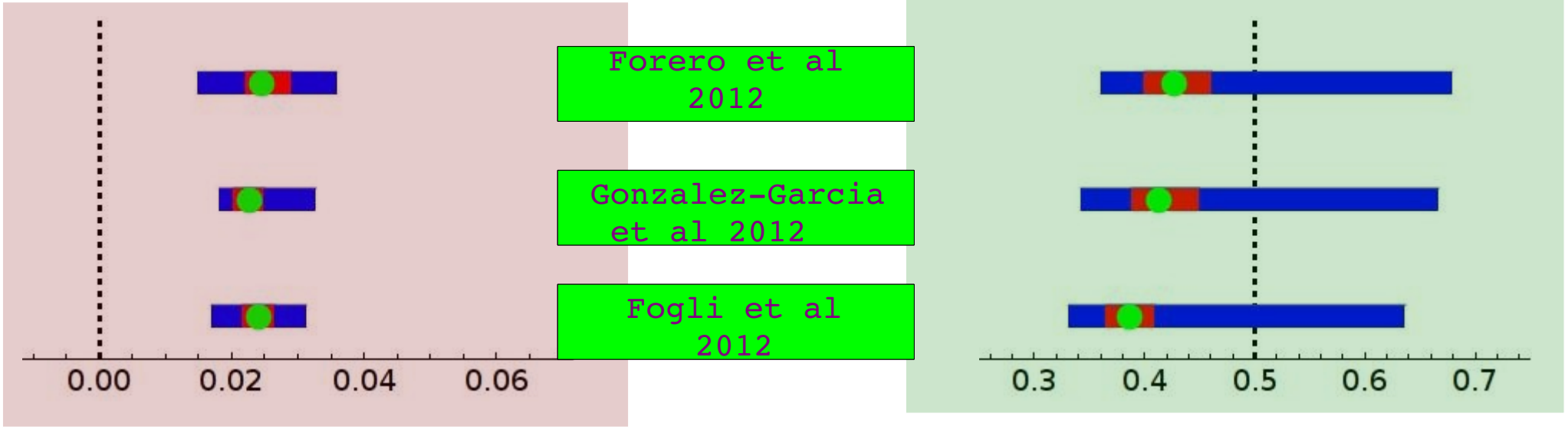


Higgs portal

Neutrino mixing

$\sin^2\theta_{12}$	0.320
$\sin^2\theta_{23}$	0.613 $(0.427)^a$
	0.600
$\sin^2\theta_{13}$	0.0246
	0.0250



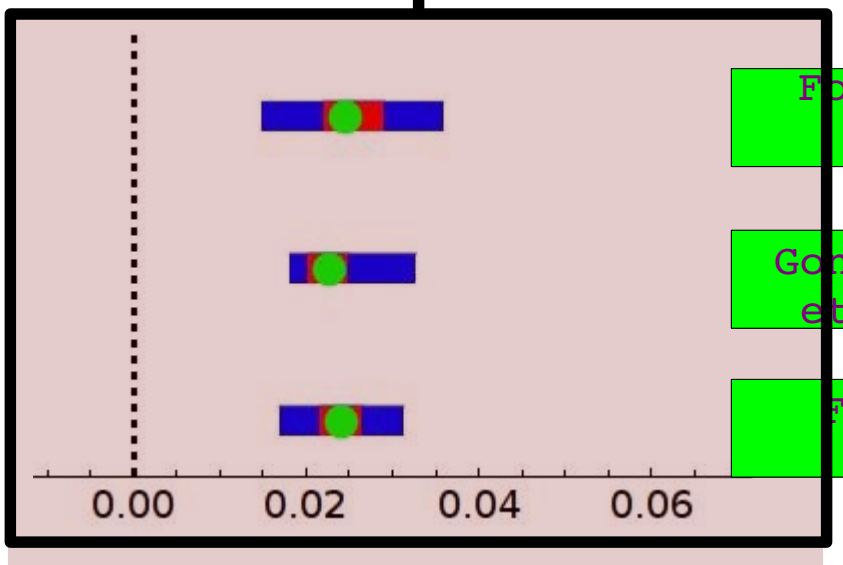


Neutrino mixing

$\sin^2\theta_{12}$	0.320
$\sin^2\theta_{23}$	0.613 $(0.427)^a$
	0.600
$\sin^2\theta_{13}$	0.0246
	0.0250

Forero et al 2012

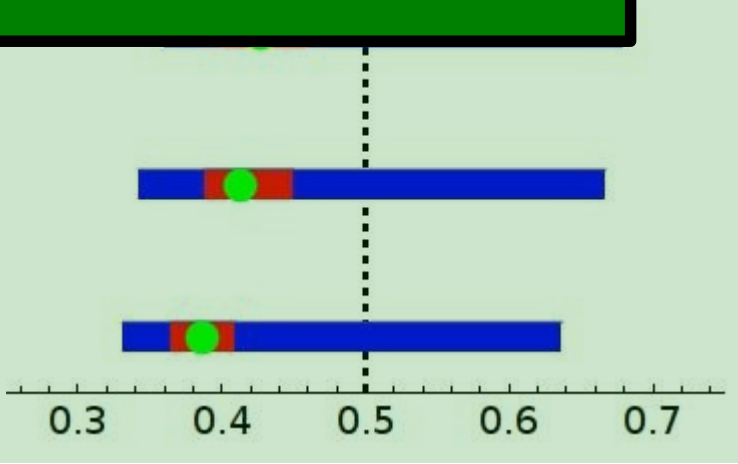
Tri-Bimaximal and all the models
Predicting **zero reactor neutrino**
RULED OUT!!!
THANKS DAYA BAY, T2K ...



Fore 2012

Gonzalez-Garcia et al 2012

Fogli et al 2012



A4 Symmetry

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

The generators are :

S and T

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

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

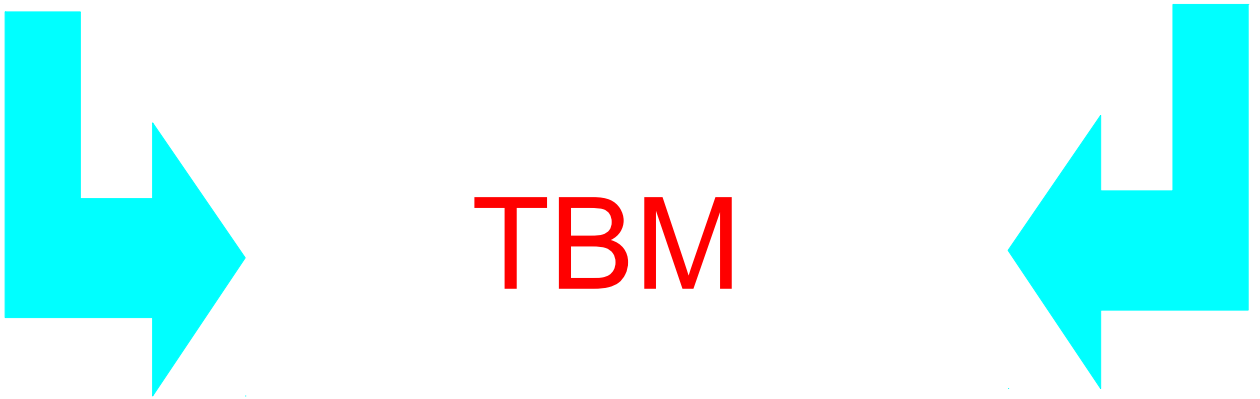
1	$S = 1$	$T = 1$
$1'$	$S = 1$	$T = e^{i4\pi/3} \equiv \omega^2$
$1''$	$S = 1$	$T = e^{i2\pi/3} \equiv \omega$

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

A4 spontaneously broken

Z3 in the charged sector

Z2 in the neutrino sector



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

A4 spontaneously broken

Z3 in the charged sector

Z2 in the neutrino sector

stabilize the DM

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

The model

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

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

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

$$1 \times 1_i = 1_i$$
$$1' \times 1'' = 1$$
$$1' \times 1' = 1''$$
$$1'' \times 1'' = 1'$$

Z_3

Charged leptons diagonal

The model

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

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

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

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

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

$\langle \eta_1^0 \rangle = v_\eta$ $\quad$ $\langle H^0 \rangle = v_h$

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

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

Neutrinos

Scaling matrix,
Rodejohan and Mohapatra

$$\begin{pmatrix} y^2 & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{pmatrix}$$

$$m_3 = 0 \qquad \begin{pmatrix} 0 \\ -c/b \\ 1 \end{pmatrix}$$

Inverse mass Hierarchy

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

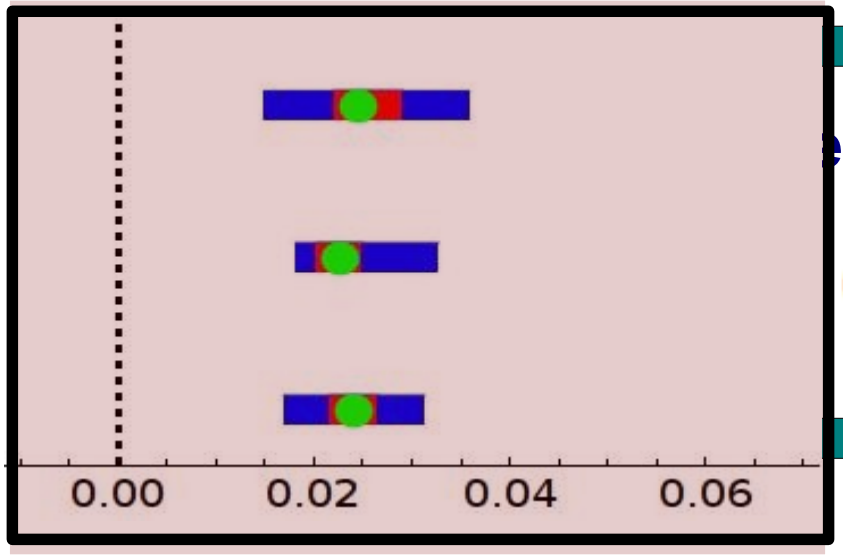
Neutrinos

Scaling matrix,
Rodejohan and Mohapatra

$$\begin{pmatrix} ac & bc & c \end{pmatrix}$$

I'll come back to this later

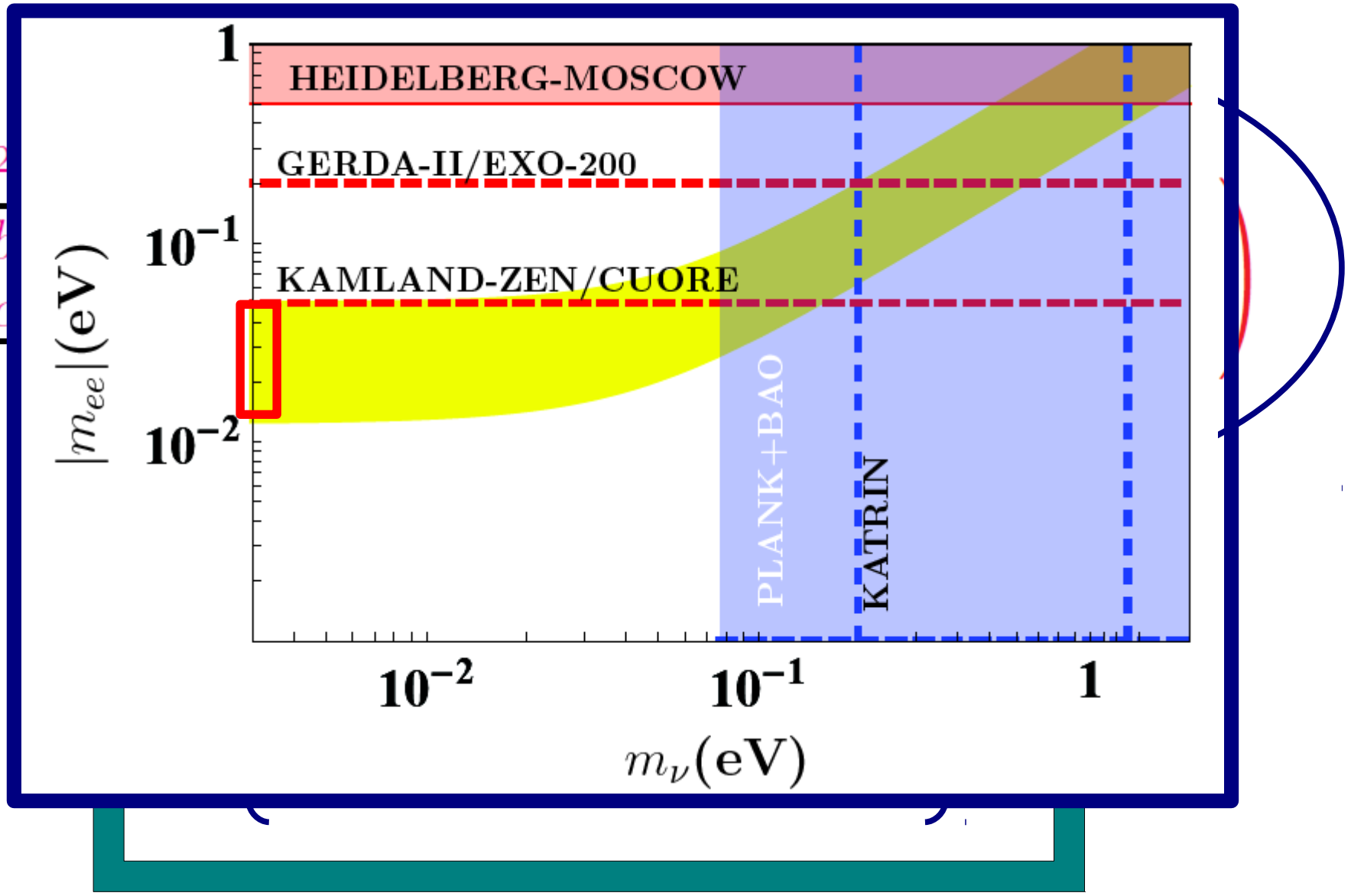
$$m_3 = 0 \qquad \begin{pmatrix} 0 \\ -c/b \\ 1 \end{pmatrix}$$



e mass Hierarchy

$0.03 - 0.05\ eV$ }

Neutrinos


HEIDELBERG-MOSCOW
GERDA-II/EXO-200
KAMLAND-ZEN/CUORE
PLANK+BAO
KATRIN
$|m_{ee}|$(eV)
m_ν(eV)
1
10^{-1}
10^{-2}
10^{-2}
10^{-1}
1

The alignment

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

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad Z_2 \quad \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} \longrightarrow \begin{pmatrix} \eta_1 \\ -\eta_2 \\ -\eta_3 \end{pmatrix}$$

$$\begin{aligned} N_2 &\to -N_2\,, & H_2 &\to -H_2\,, & A_2 &\to -A_2 \\ N_3 &\to -N_3\,, & H_3 &\to -H_3\,, & A_3 &\to -A_3 \end{aligned}$$

Z_2 residual symmetry

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

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

$$H = \begin{pmatrix} \tilde{H}_0^+ \\ (v_h + \tilde{H}_0 + i\tilde{A}_0)/\sqrt{2} \end{pmatrix}, \quad \eta_1 = \begin{pmatrix} \tilde{H}_1^+ \\ (v_\eta + \tilde{H}_1 + i\tilde{A}_1)/\sqrt{2} \end{pmatrix}$$

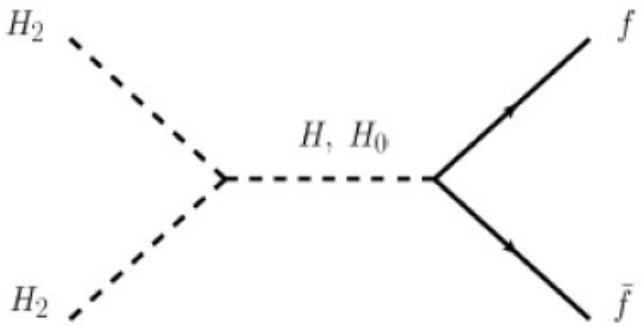
Z2 even

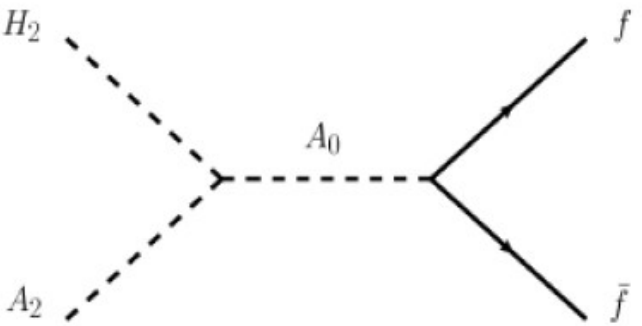
$$\eta_2 = \begin{pmatrix} \tilde{H}_2^+ \\ (\tilde{H}_2 + i\tilde{A}_2)/\sqrt{2} \end{pmatrix}, \qquad \eta_3 = \begin{pmatrix} \tilde{H}_3^+ \\ (\tilde{H}_3 + i\tilde{A}_3)/\sqrt{2} \end{pmatrix}$$

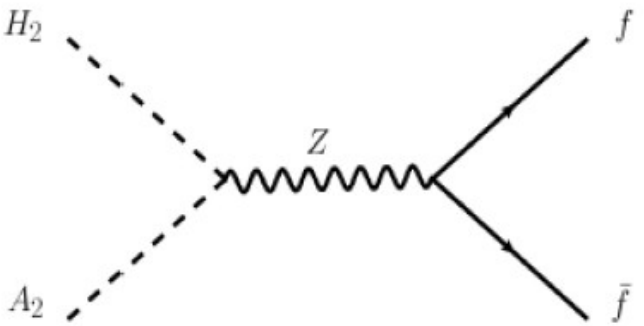
Z2 odd

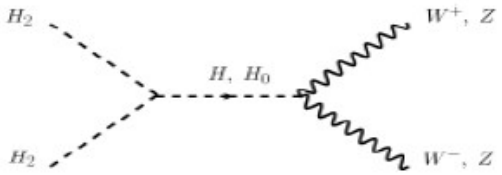
Dark Matter Stability

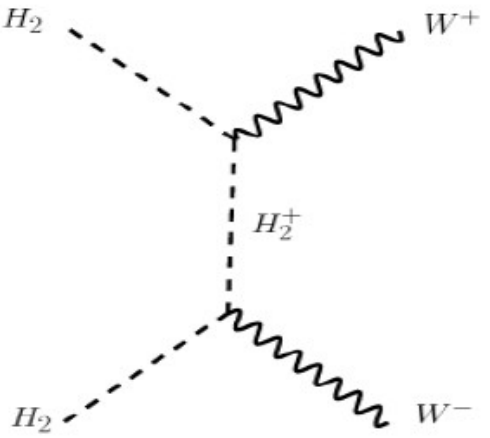
Relevant Diagrams

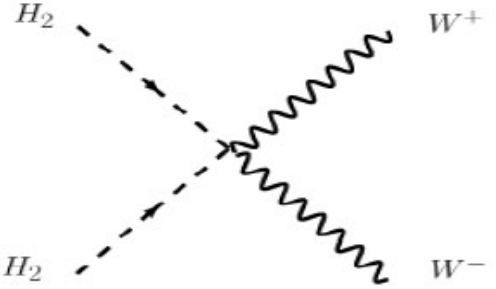


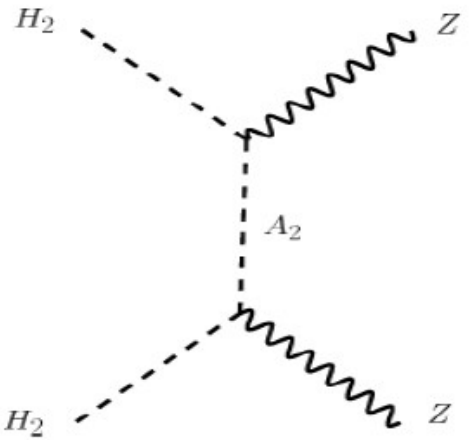












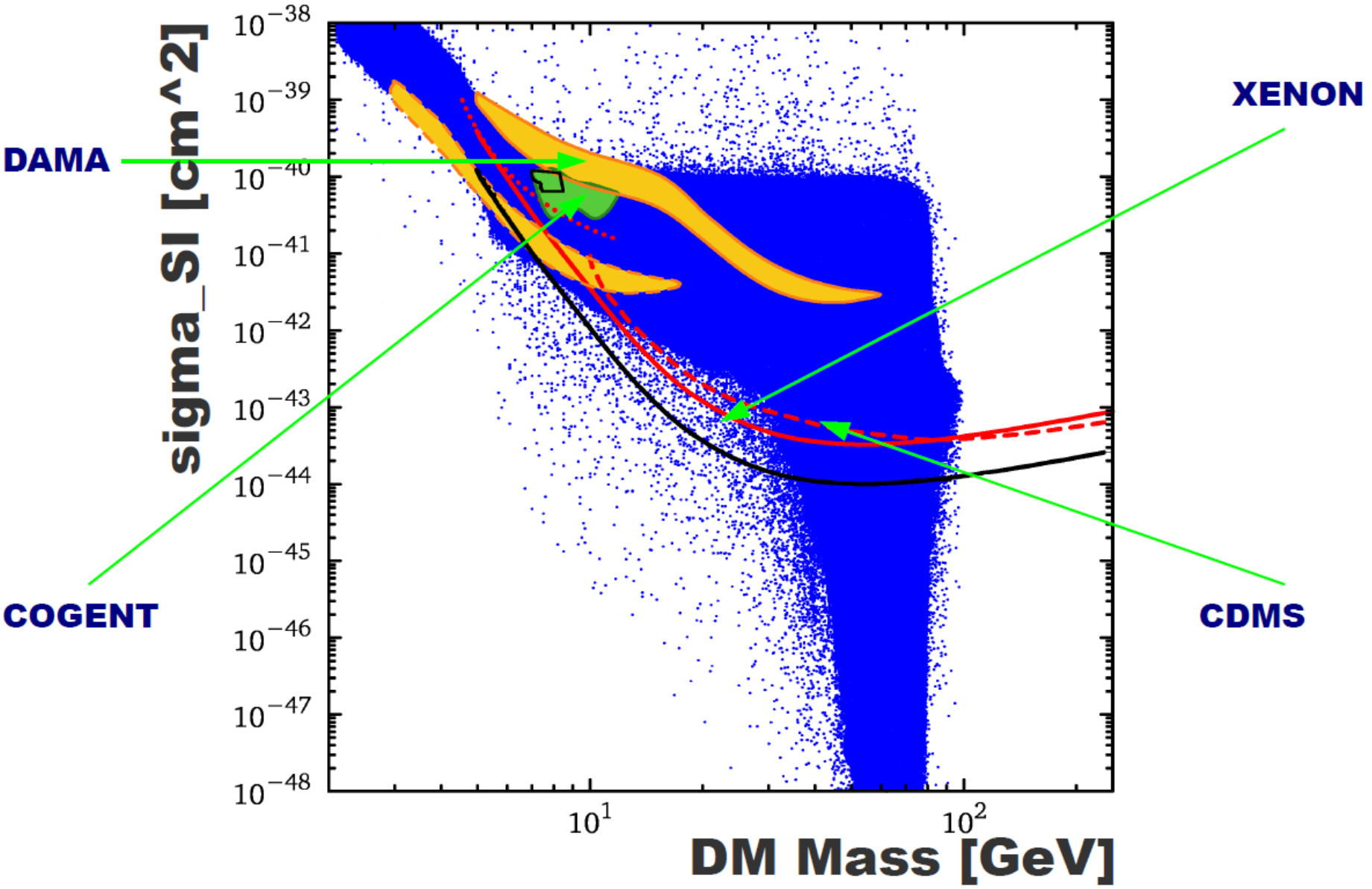
Boucenna, Hirsch, Morisi, Peinado, Taoso and Valle
JHEP 1105 (2011) 037

Constraints

- Relic Density
- Collider bounds
- EW precision
- Vacuum stability
- Perturbativity

Boucenna, Hirsch, Morisi, Peinado, Taoso and Valle
JHEP 1105 (2011) 037

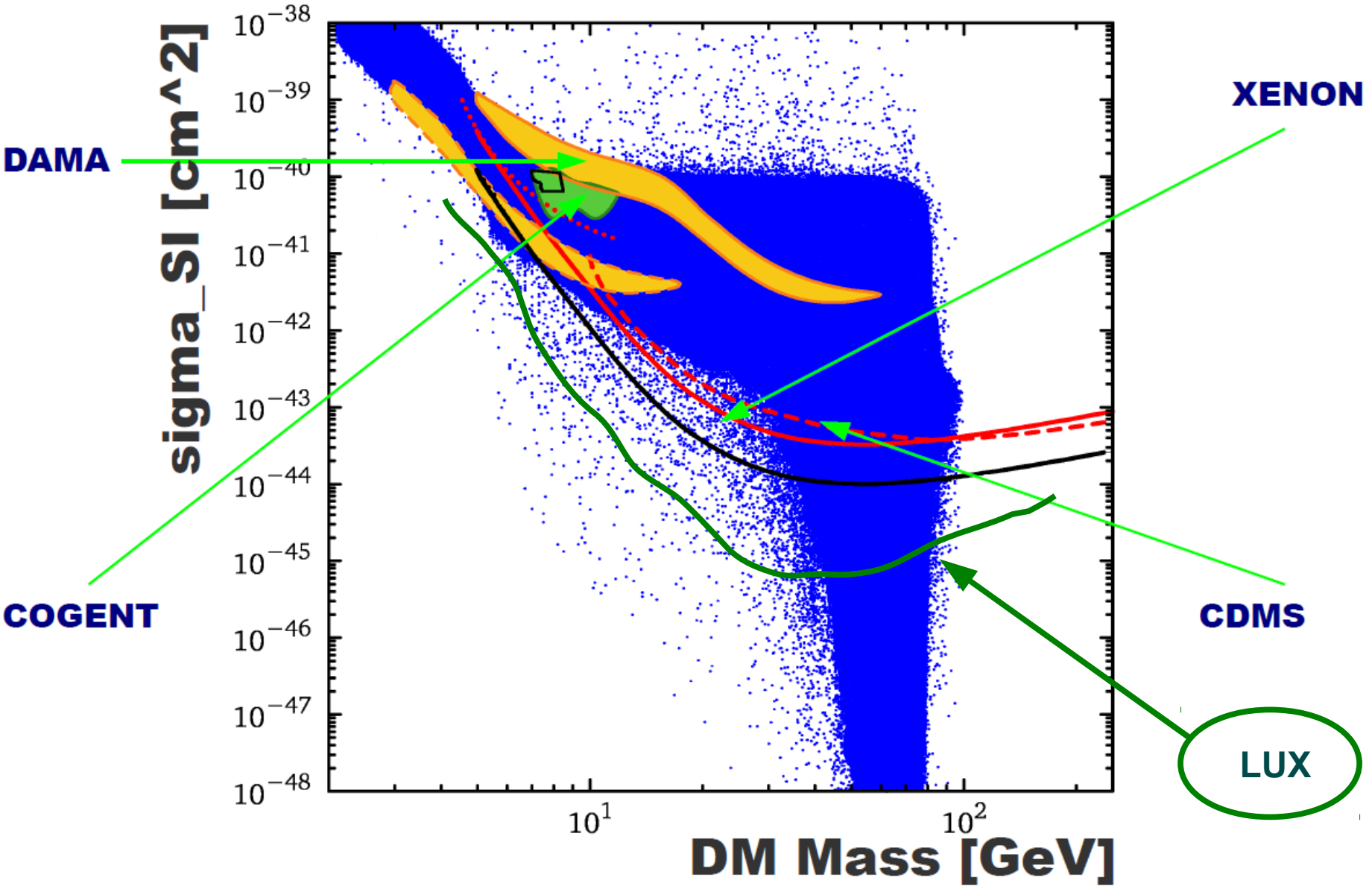
Direct detection



... Direct Detection

JHEP 1105 (2011) 037

Direct detection



... Direct Detection

LUX collaboration
arXiv:1310.8214

Reactor mixing angle

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

D4

m1=0 θ_{13}=0

Meloni, Morisi, Peinado
Phys.Lett. B703 (2011) 281-287

Reactor mixing angle

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

S3

m1=0

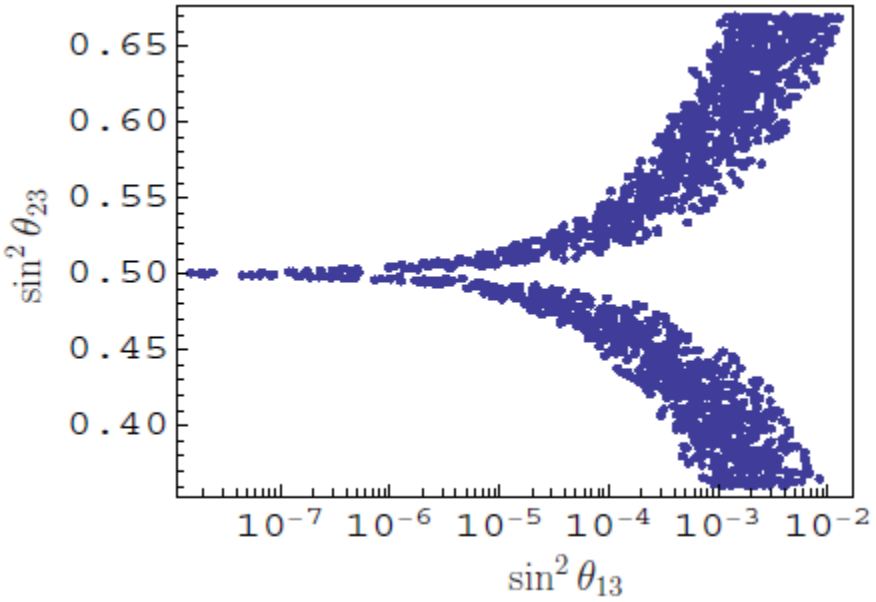
Meloni, Morisi, Peinado didn't send to publication (too boring) :(

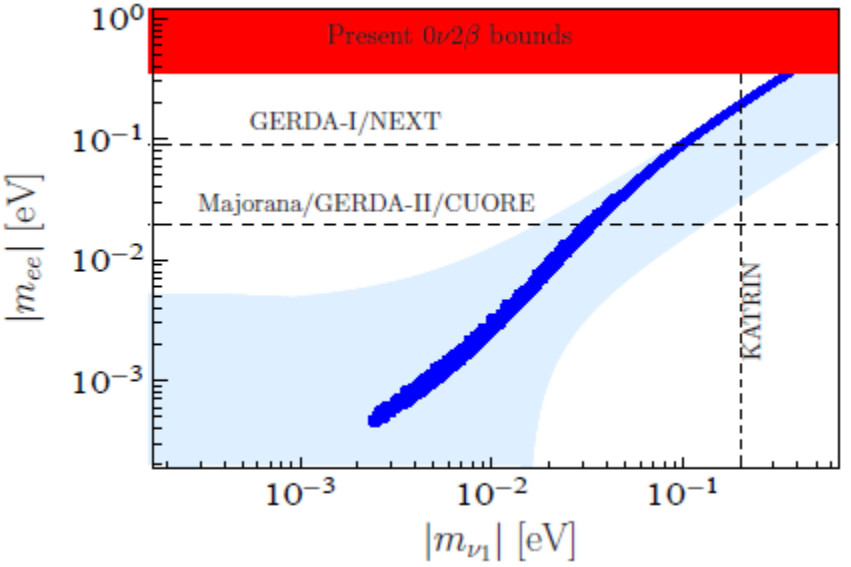
Reactor mixing angle

In this kind of models, not only with A4 but D4 and even S3 the prediction is zero reactor mixing angle ….

We did a first attempt before T2K and found a correlation among the mixing angles

Meloni, Morisi, Peinado
arXiv:1011.1371
Phys.Lett. B697 (2011) 339-342





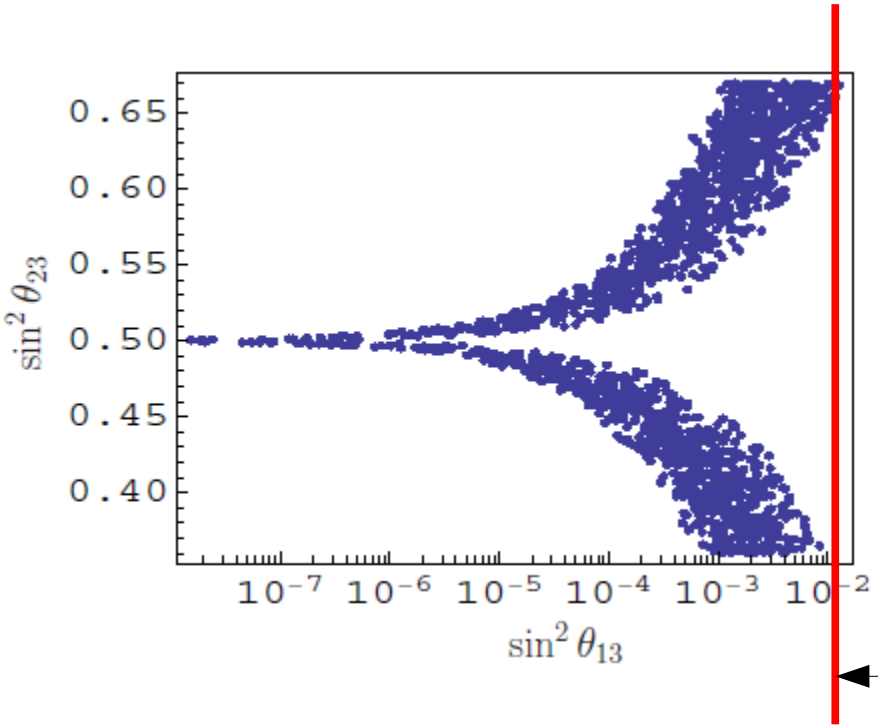
Reactor mixing angle

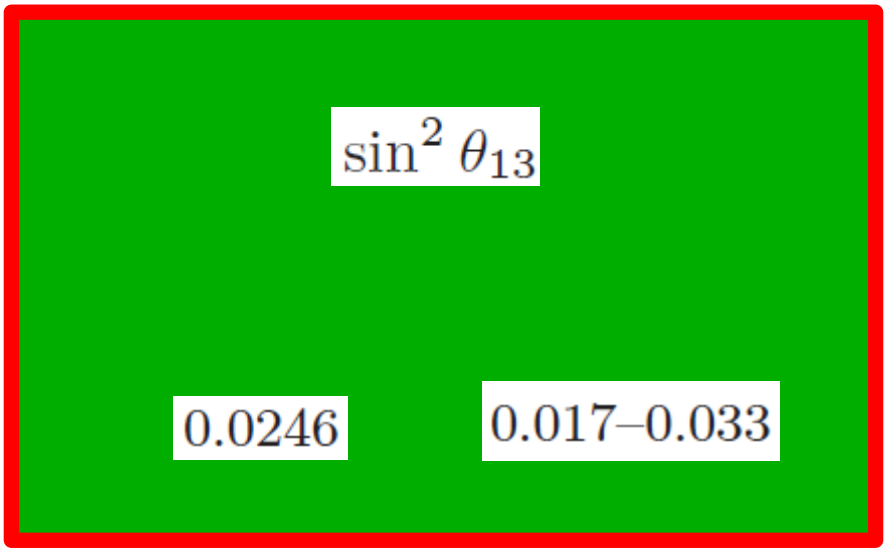
In this kind of models, not only with A4 but D4 and even S3 the prediction is zero reactor mixing angle ….

Meloni, Morisi, Peinado
Phys.Lett. B703 (2011) 281-287

We did a first attempt much before T2K and found a correlation among the mixing angles

Meloni, Morisi, Peinado
arXiv:1104.0178
Phys.Lett. B697 (2011) 339-342





0.01

Reactor mixing angle

Hamada, *et. al.* Arxiv:1405.3592

Revisiting Discrete Dark Matter Model:
$\theta_{13} \neq 0$ and ν_R Dark Matter

Radiative corrections to neutrino masses, soft A4 breaking in the potential and extra right-handed neutrinos

The model for reactor mixing angle

Peinado, in progress...

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

Charged leptons diagonal

Now the FS will be broken At the see-saw scale

The model for reactor mixing angle

Peinado, in progress...

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

Charged leptons diagonal

Now the FS will be broken At the see-saw scale

$$V_{lep} = U_l^+ U_\nu$$

Neutrino masses

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

η

ϕ

$(1,0,0)$

$$V_{lep} = U_l^+ \, U_\nu$$

$$m_\nu = -m_{D_{3\times5}} M^{-1}_{R_{5\times5}} m^T_{D_{3\times5}} \equiv \begin{pmatrix} a & 0 & b \\ 0 & 0 & c \\ b & c & d \end{pmatrix}$$

Two zero-textures
B3

Frampton, Glashow, Marfatia

Merle, Rodejohann

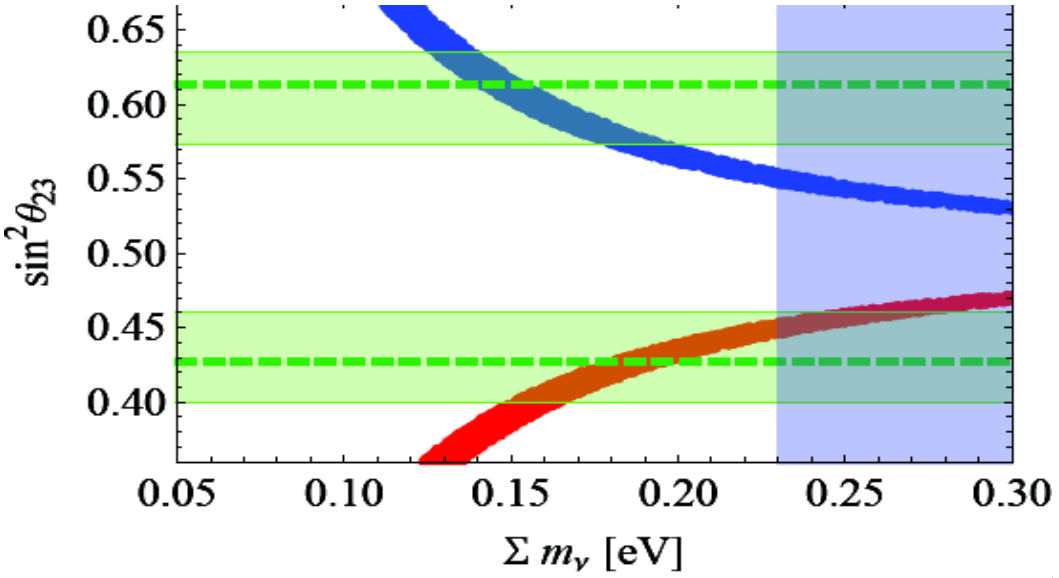
Ludl, Morisi, Peinado

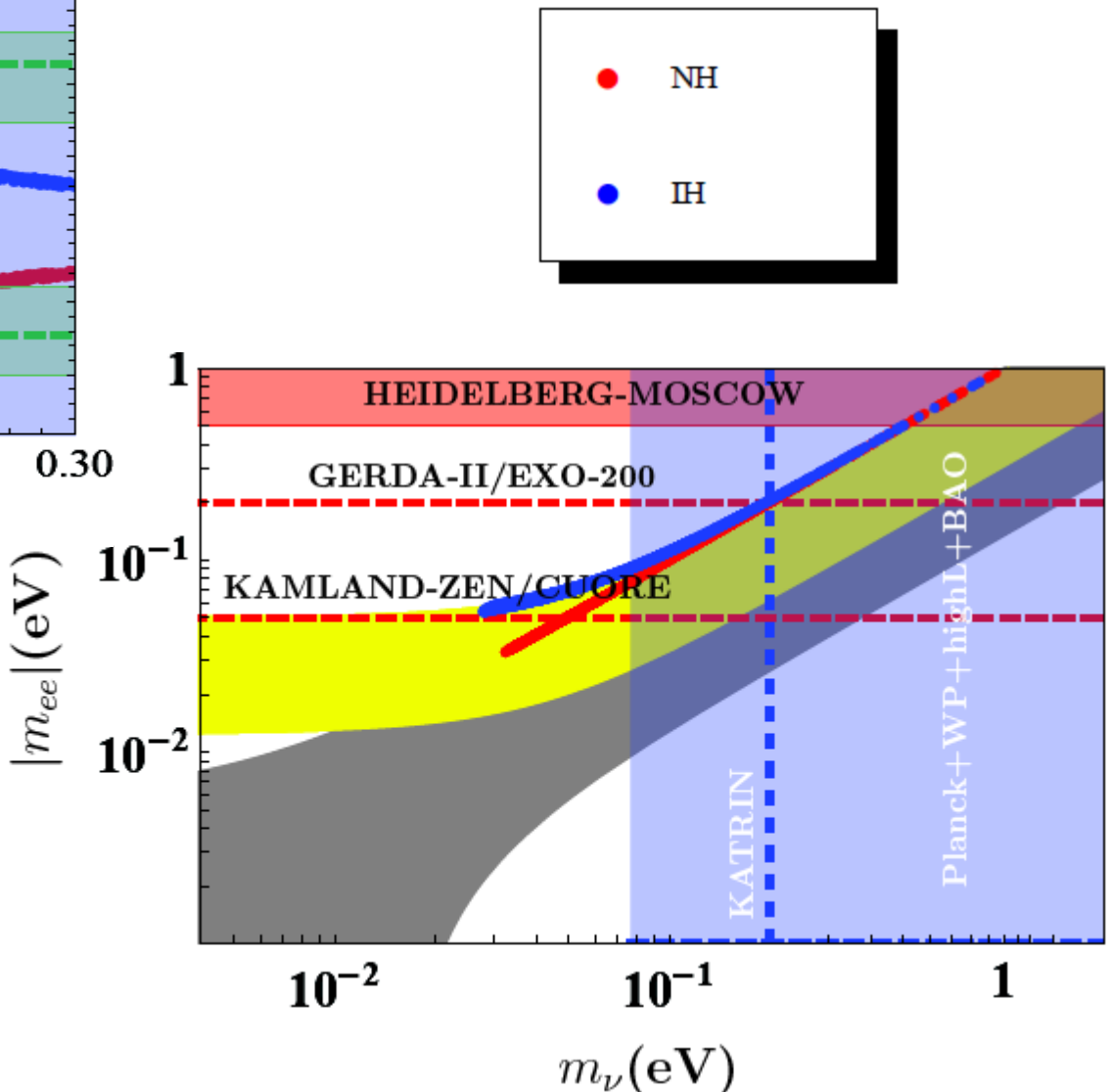
……..

See talk by Ludl

Normal spectrum

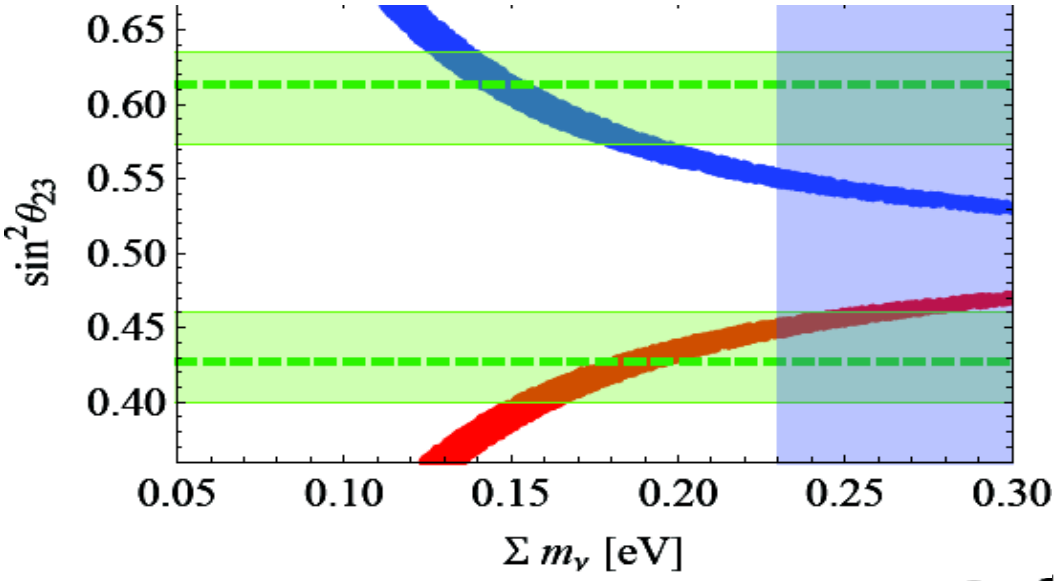
Normal Hierarchy

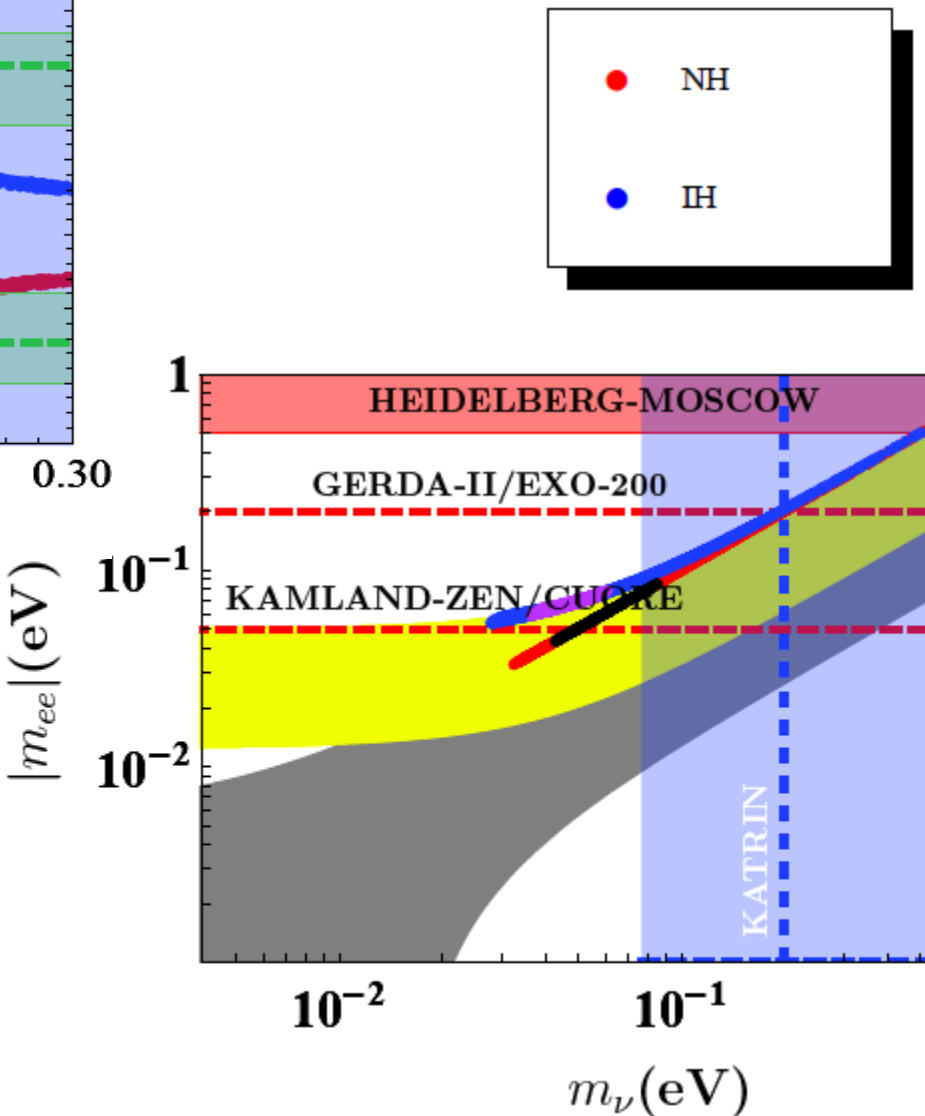




Normal spectrum

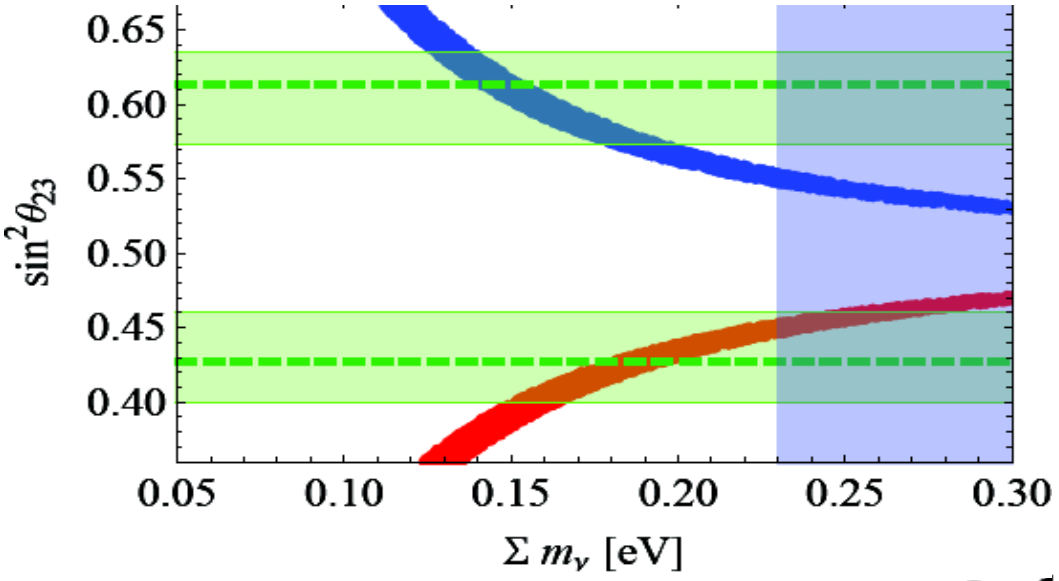
Normal Hierarchy

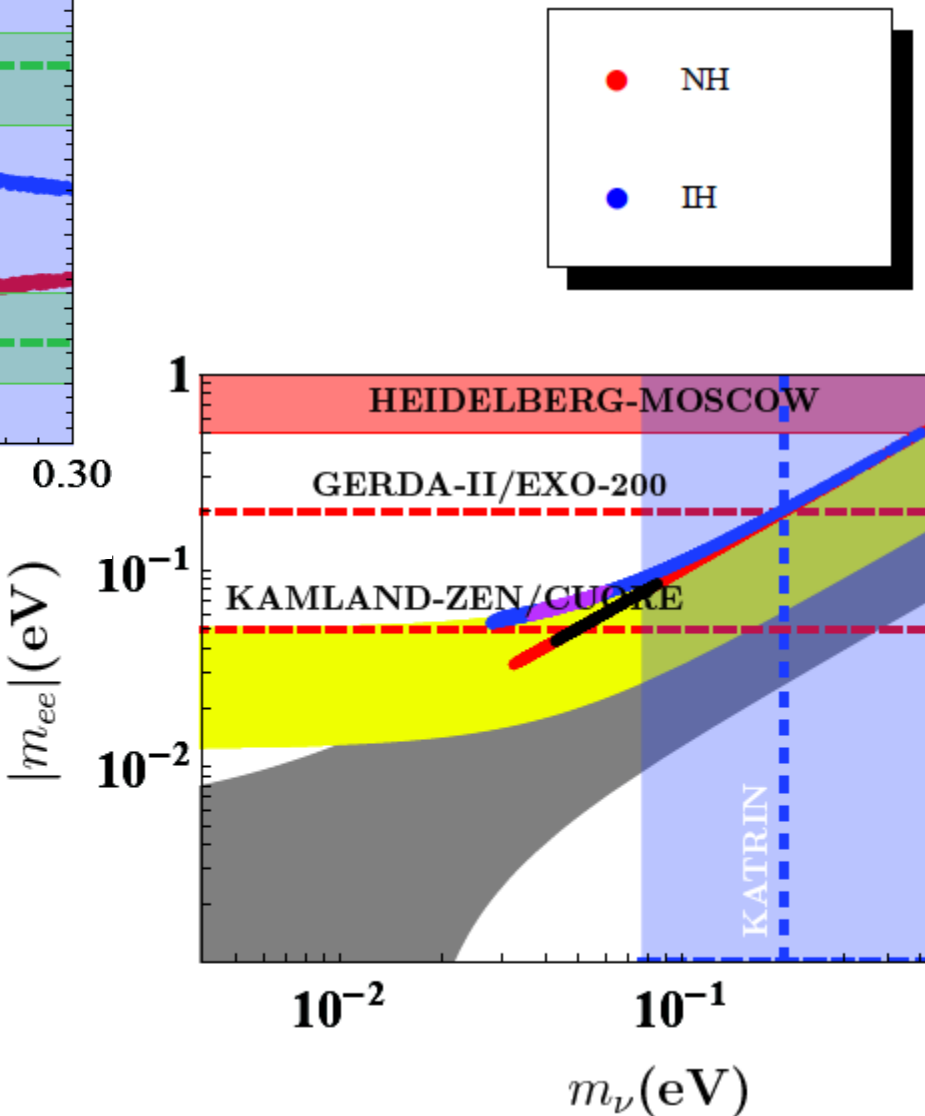




Normal spectrum

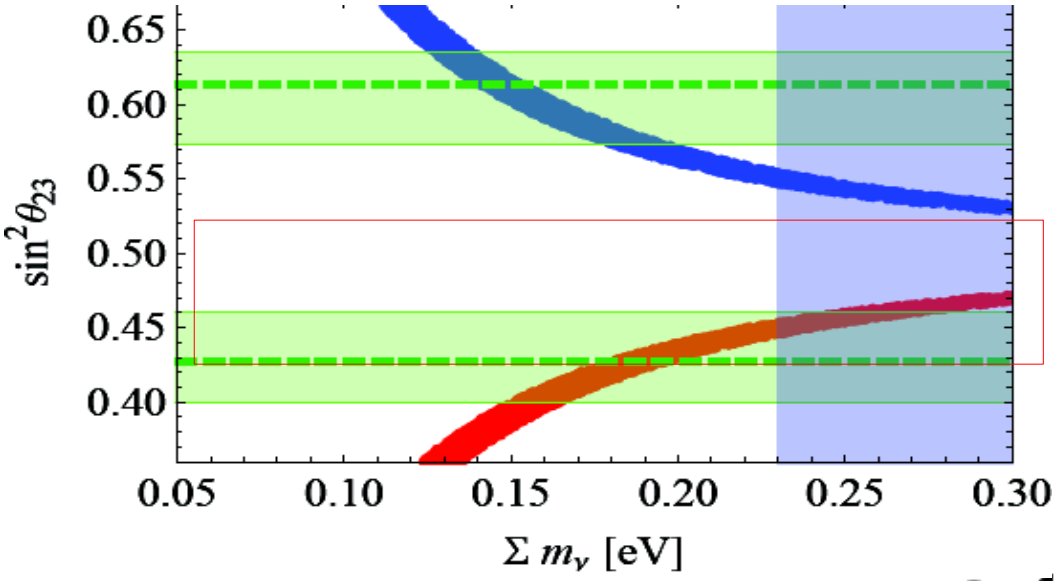
Normal Hierarchy



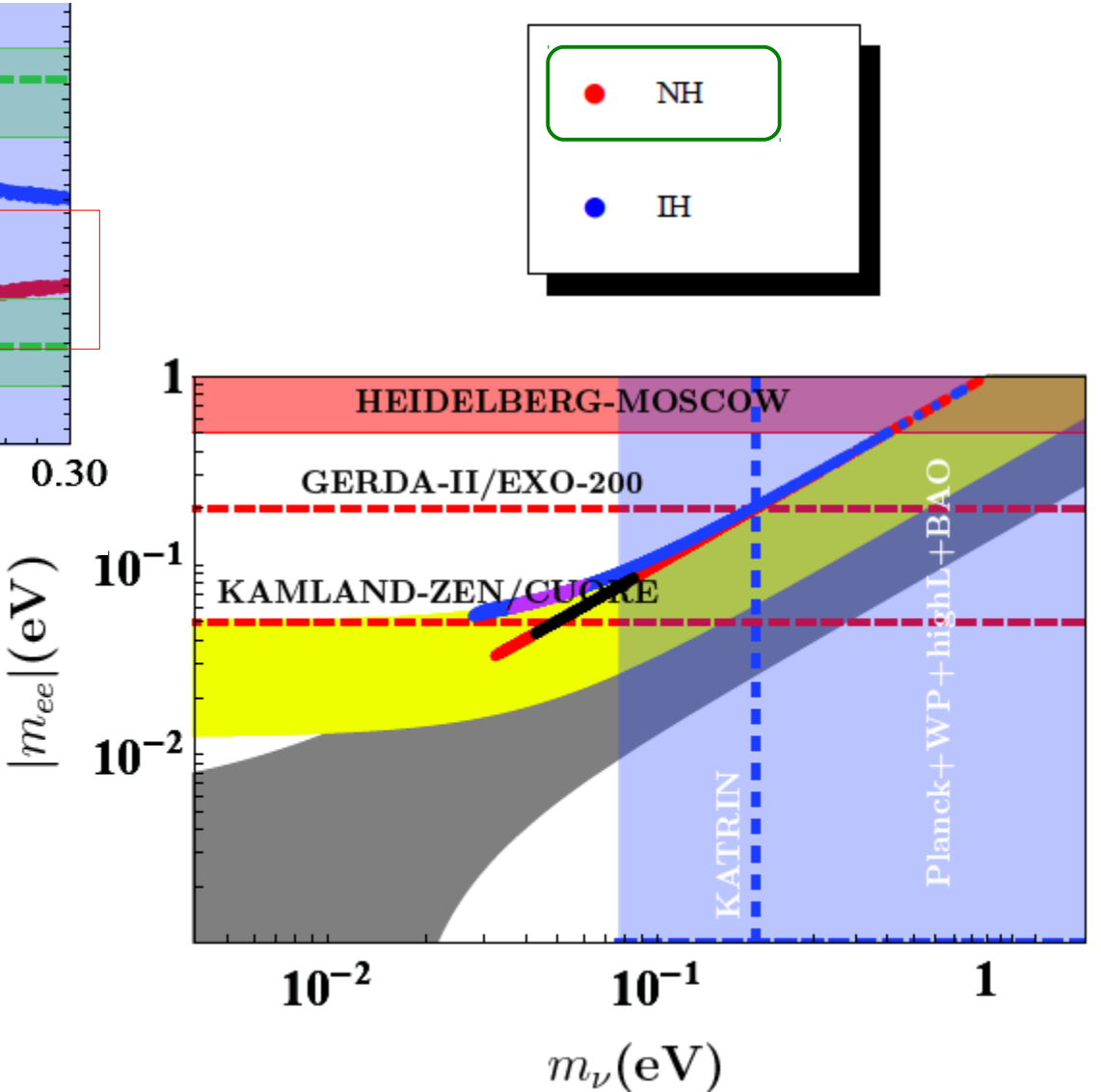


Normal spectrum

Normal Hierarchy

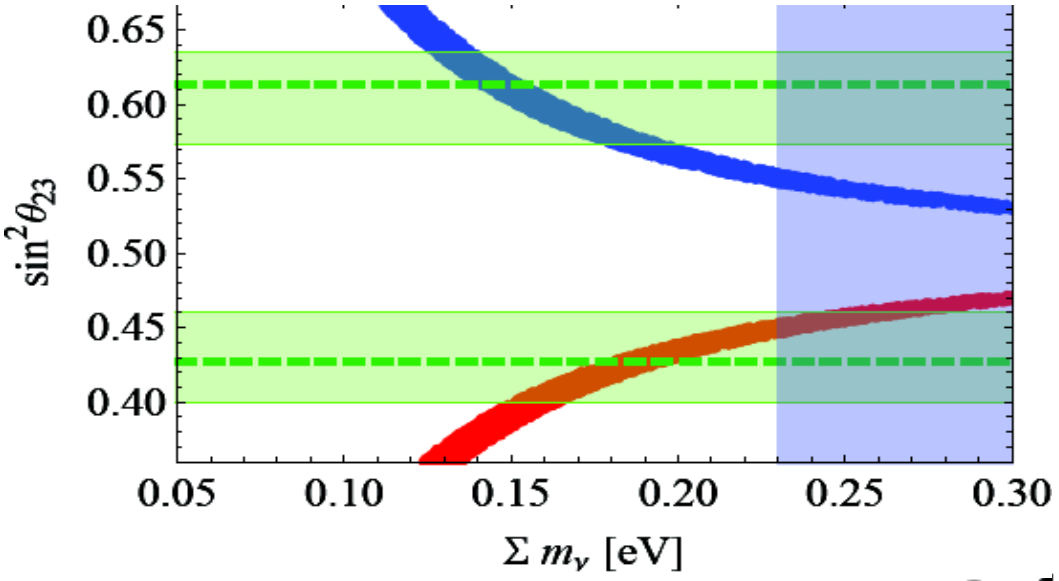


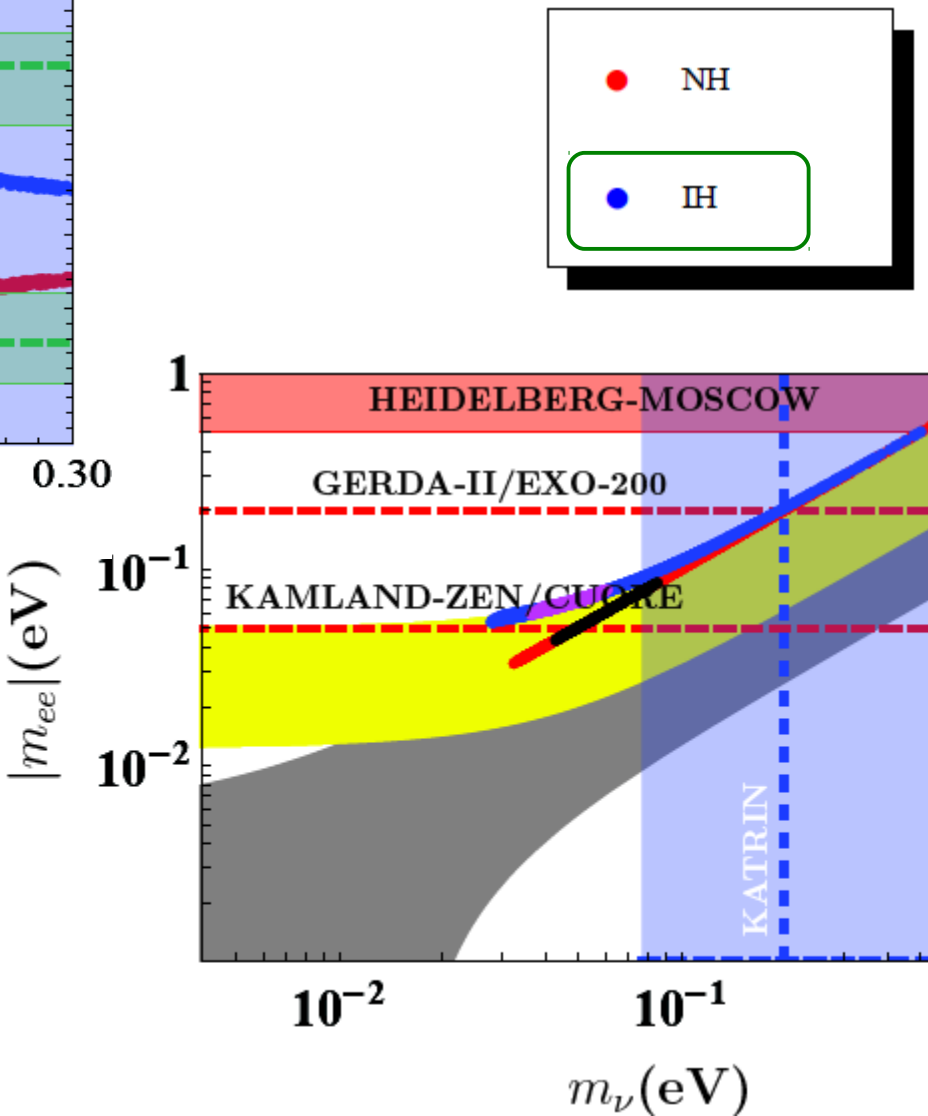
1σ range	
4.39–5.99	$\sin^2\theta_{23}/10^{-1}$ (NH)
5.30–5.98	$\sin^2\theta_{23}/10^{-1}$ (IH)



Inverted spectrum

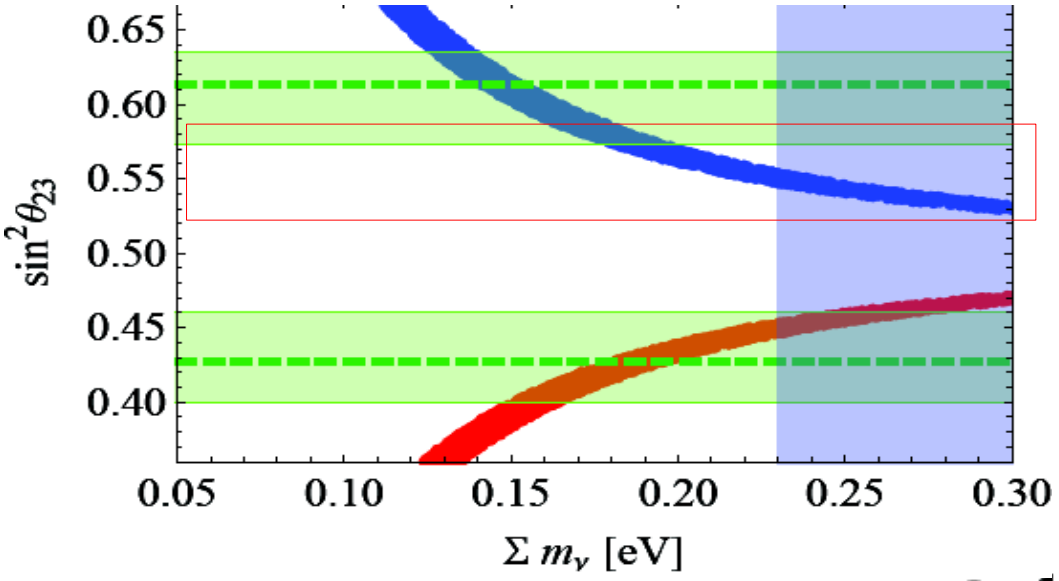
Inverted Hierarchy



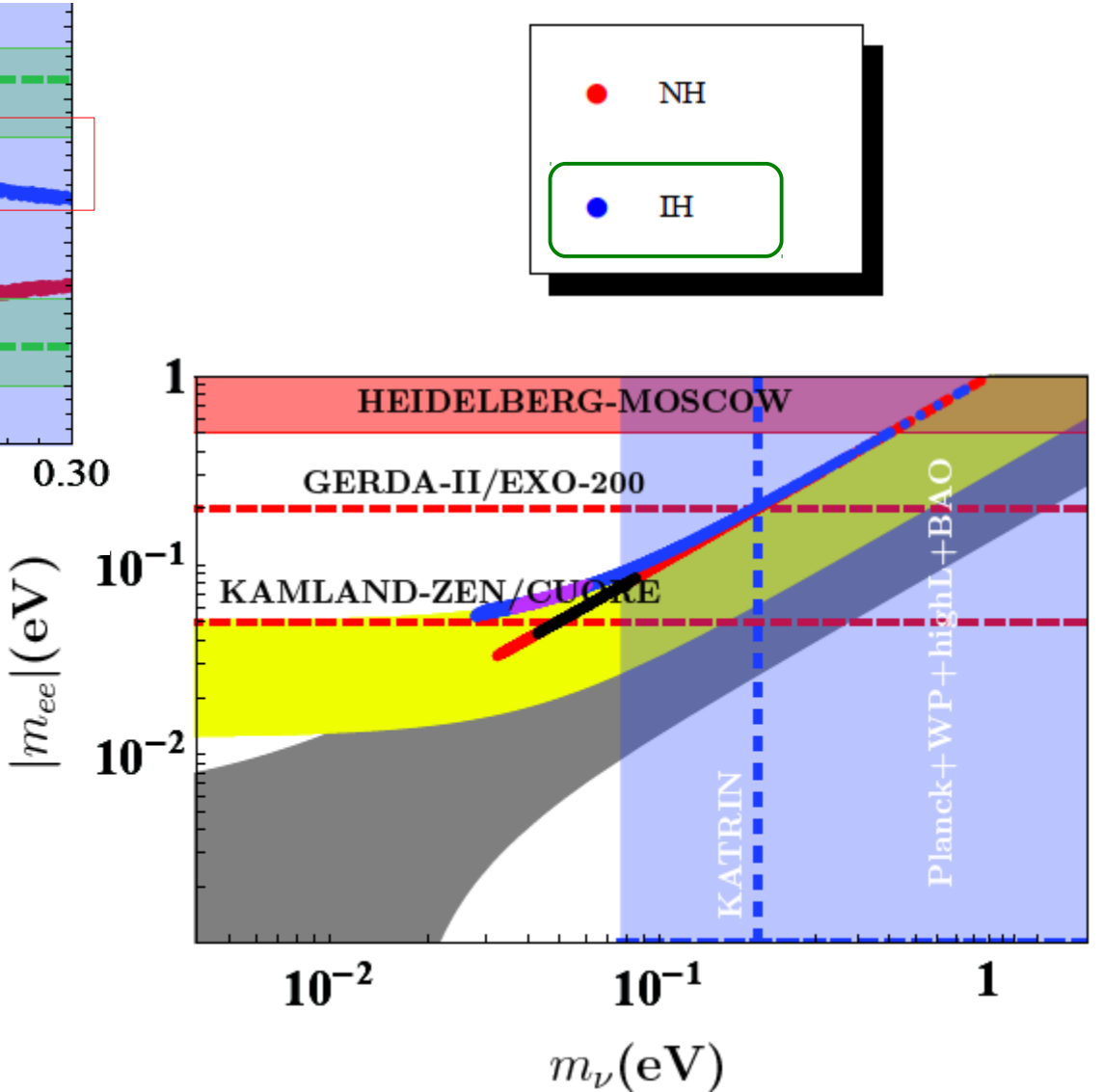


Inverted spectrum

Inverted Hierarchy



1σ range	
4.39–5.99	$\sin^2\theta_{23}/10^{-1}$ (NH)
5.30–5.98	$\sin^2\theta_{23}/10^{-1}$ (IH)



Conclusions I

- It is interesting to find models where connections among phenomenas
  - Neutrinos and DM
- A flavor symmetry can account for the DM stability and at the same time for the neutrino masses and mixings
  - FS vs Z2 ----> high mass region
- Is it possible to connect also the BAU?

Thank you very much for your attention