Neutrinos and its possible connection with DM

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Mazatlan, Sinaloa

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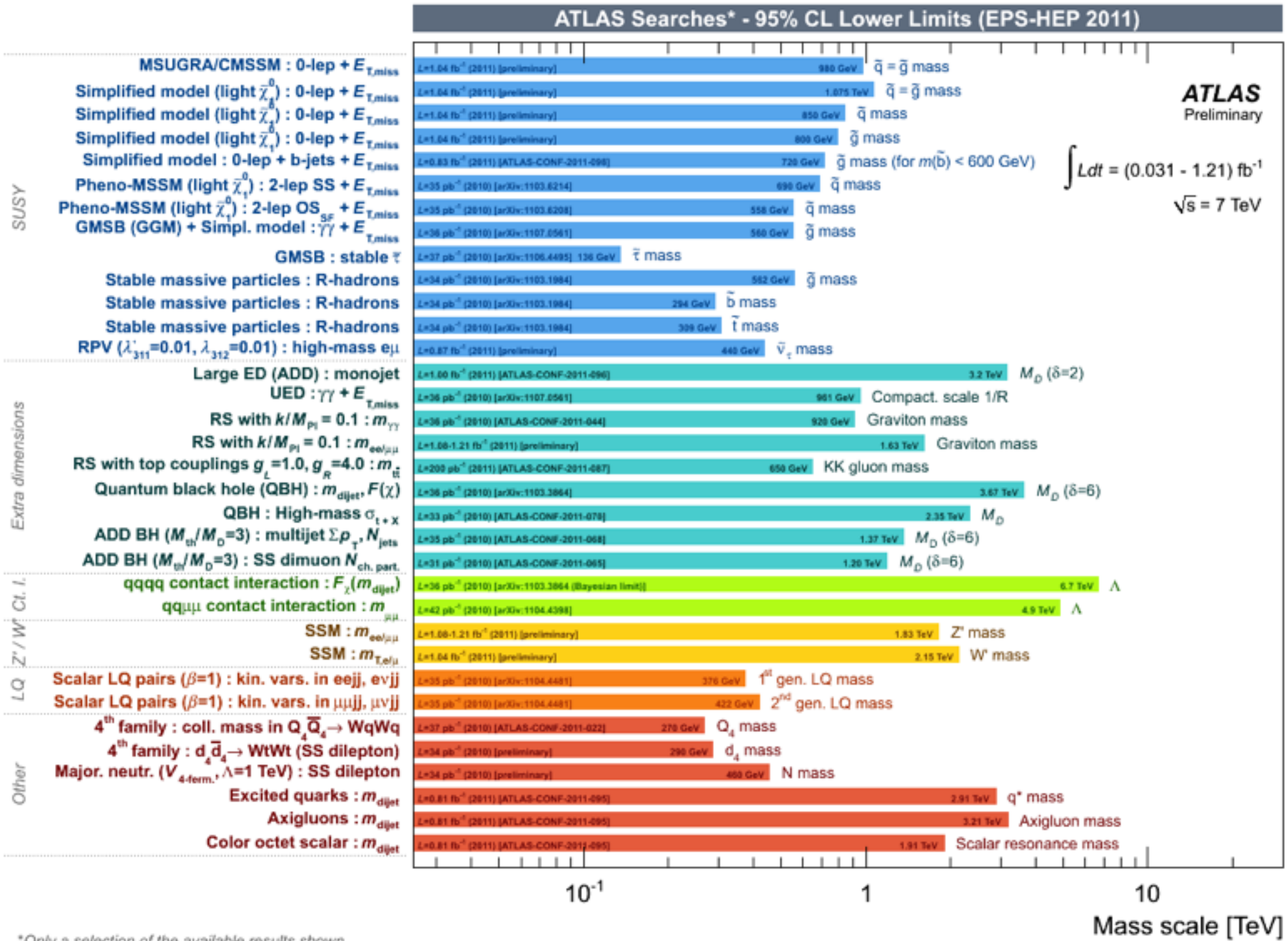
BSM

Limits on some scenarios by LCH



The SM is complete LHC

The SM is complete LHC

Terra cognita and terra incognita

The SM is complete LHC

Terra cognita and terra incognita

Standard Model & Physics BSM

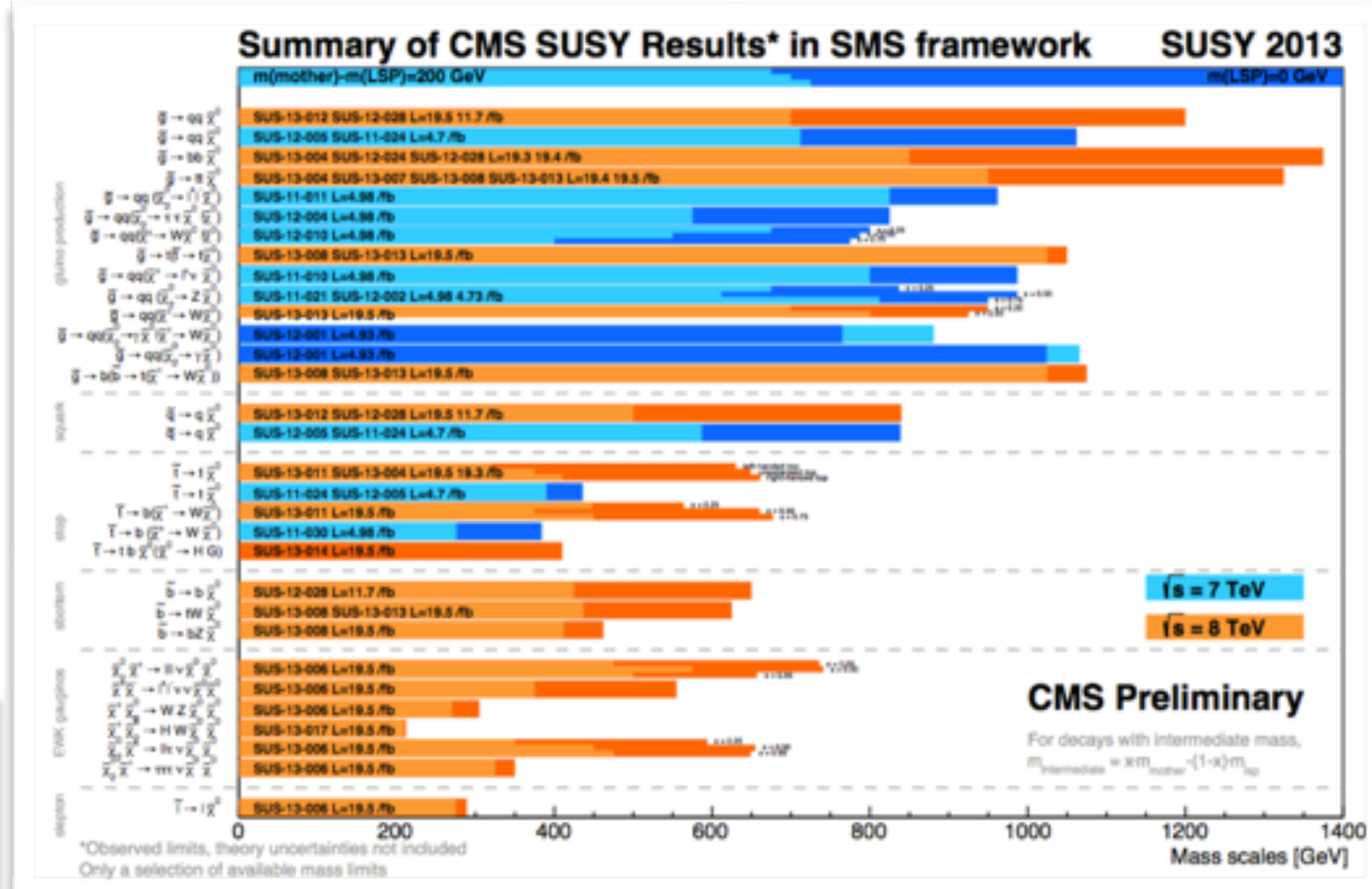
Infinite possibilities

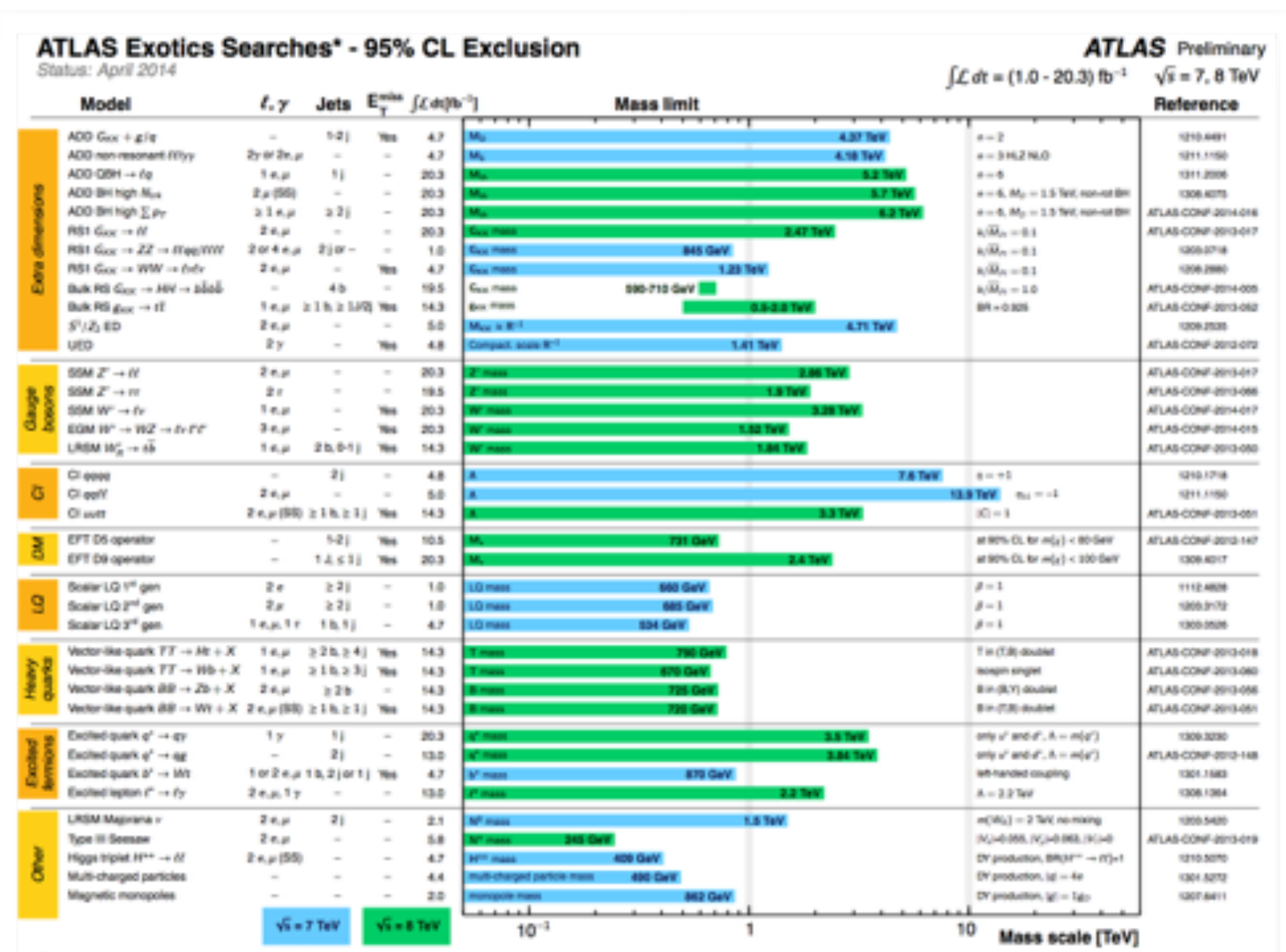
H. Murayama

- Many of these extensions were proposed to address some unsolved questions of the SM: hierarchy problem, generation and flavour problem
- Others simply to explain some deviations of the SM, top forward backward asymmetry, $\mu \to e\gamma$, $h \to \gamma\gamma$, non universal lepton decays, DM, etc…

BSM searches

Nothing yet!!!





Only limits!!!
(and possible hints)

Outline

- **Introduction**

  The SM

- **Neutrino physics**

  SeeSaw Mechanism

- **Extensions of the SM**

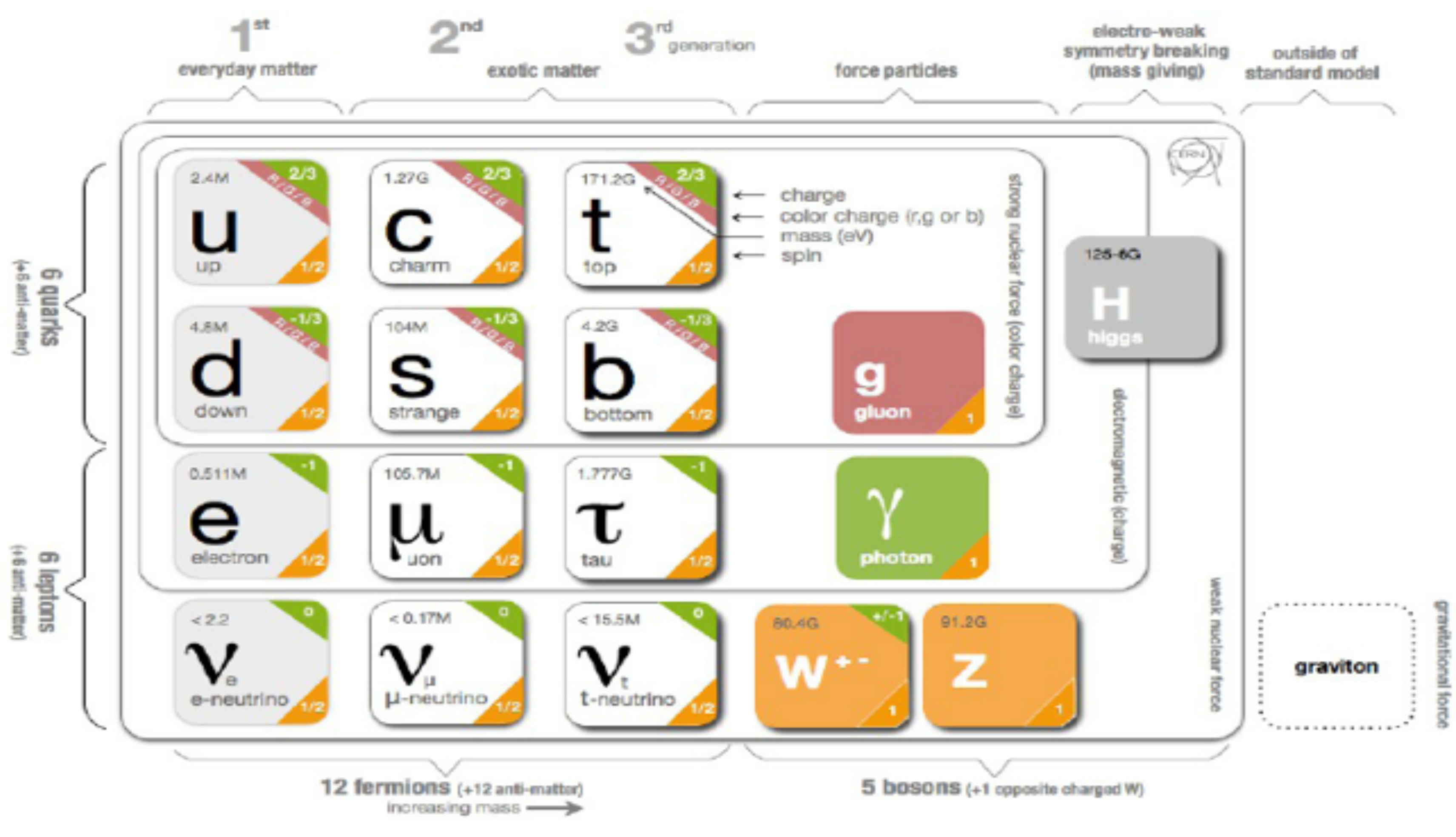
  Using neutrinos

- **Conclusions**

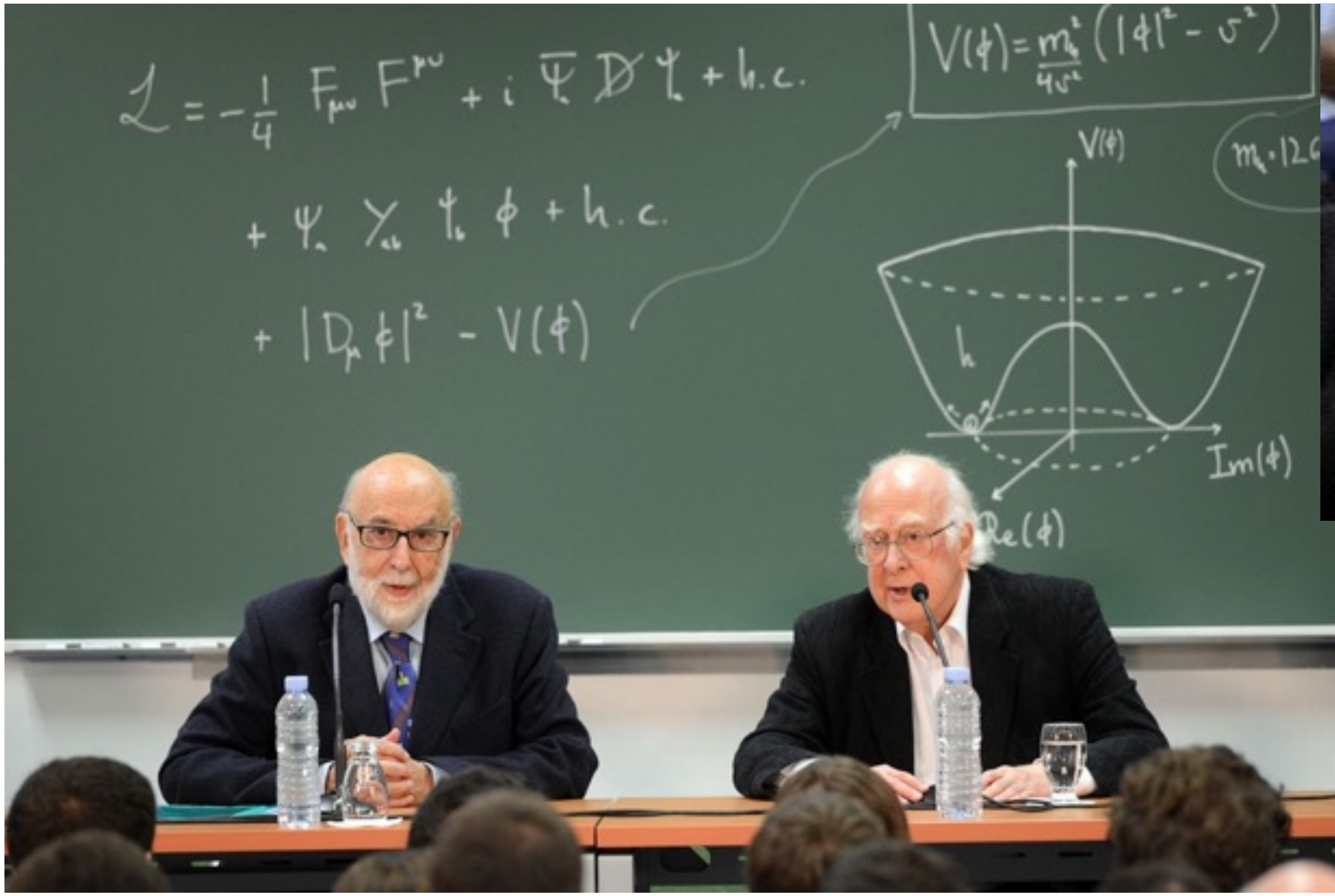
The SM

$$SU_c(3) \times SU_L(2) \times U_Y(1)$$

"Mendeleev periodic table" for high energy physics



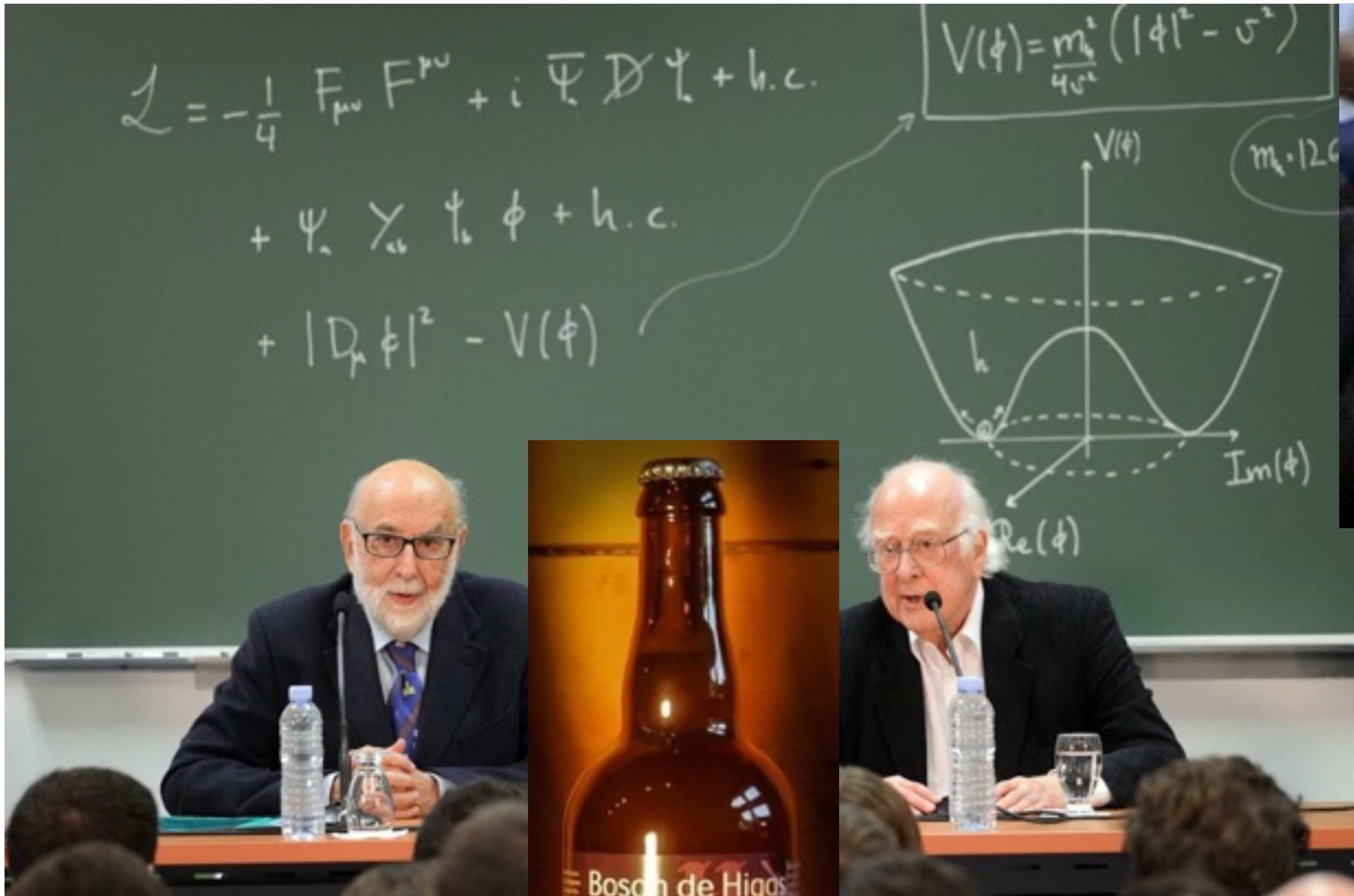
The SM



Fundación principe de Asturias

Cern Higgs Discovery

The SM

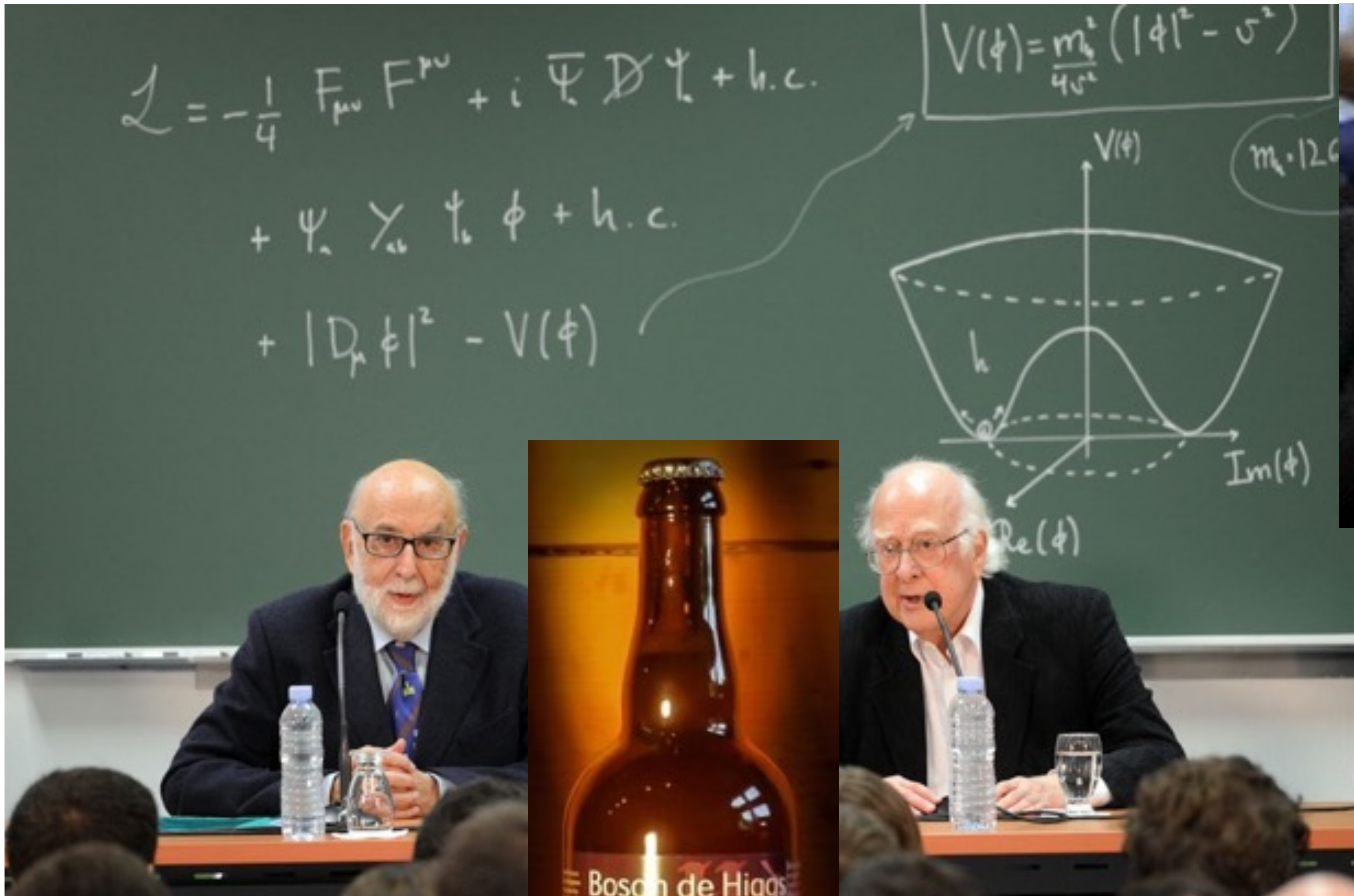


Fundación principe de Astu

Cern Higgs Discovery

What about
neutrino masses?
DM?
BAU?
etc…

The SM



Fundación principe de Astu

Cern Higgs Discovery

with flavor?

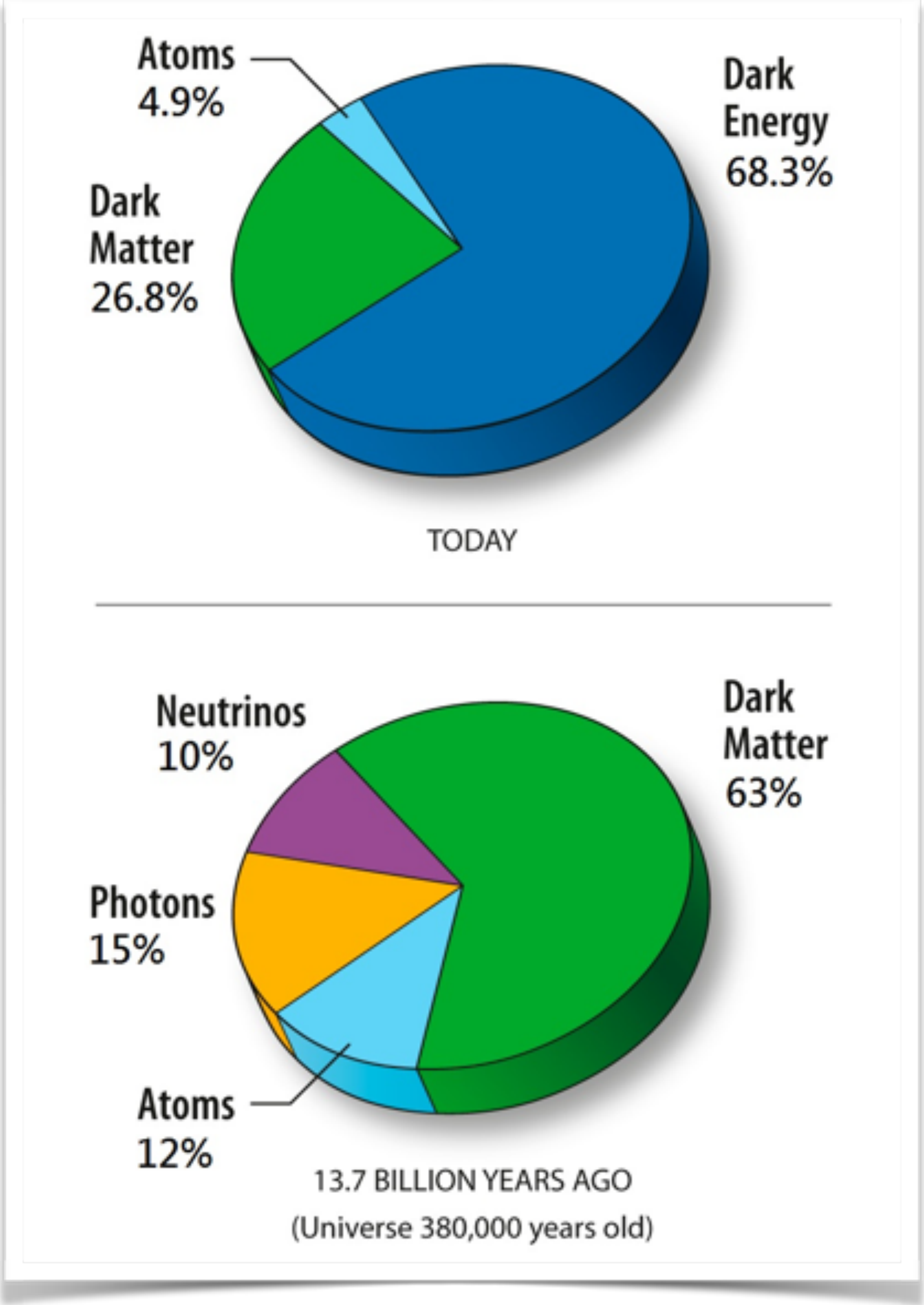
What about
neutrino masses?
DM?
BAU?
etc…

Evidence of Physics BSM

Jose's talk

Eric's talk

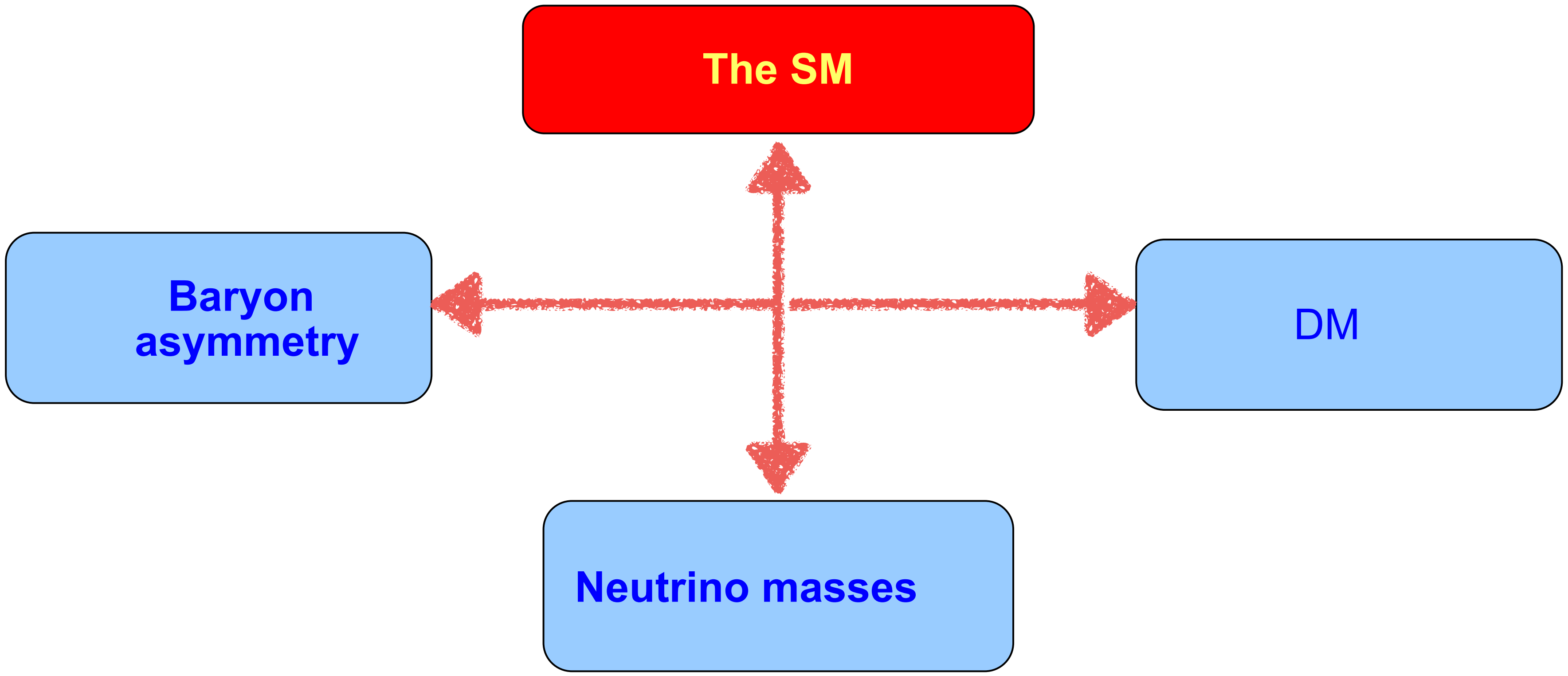
- LHC put constraints only in PBSM
- Neutrino masses * (In the SM L is not violated)
- Cosmology: Dark Matter, Baryon Asymmetry, Dark Energy …
- Some theoretical aspects like hierarchy problem
- something else? LHC? rare decays …



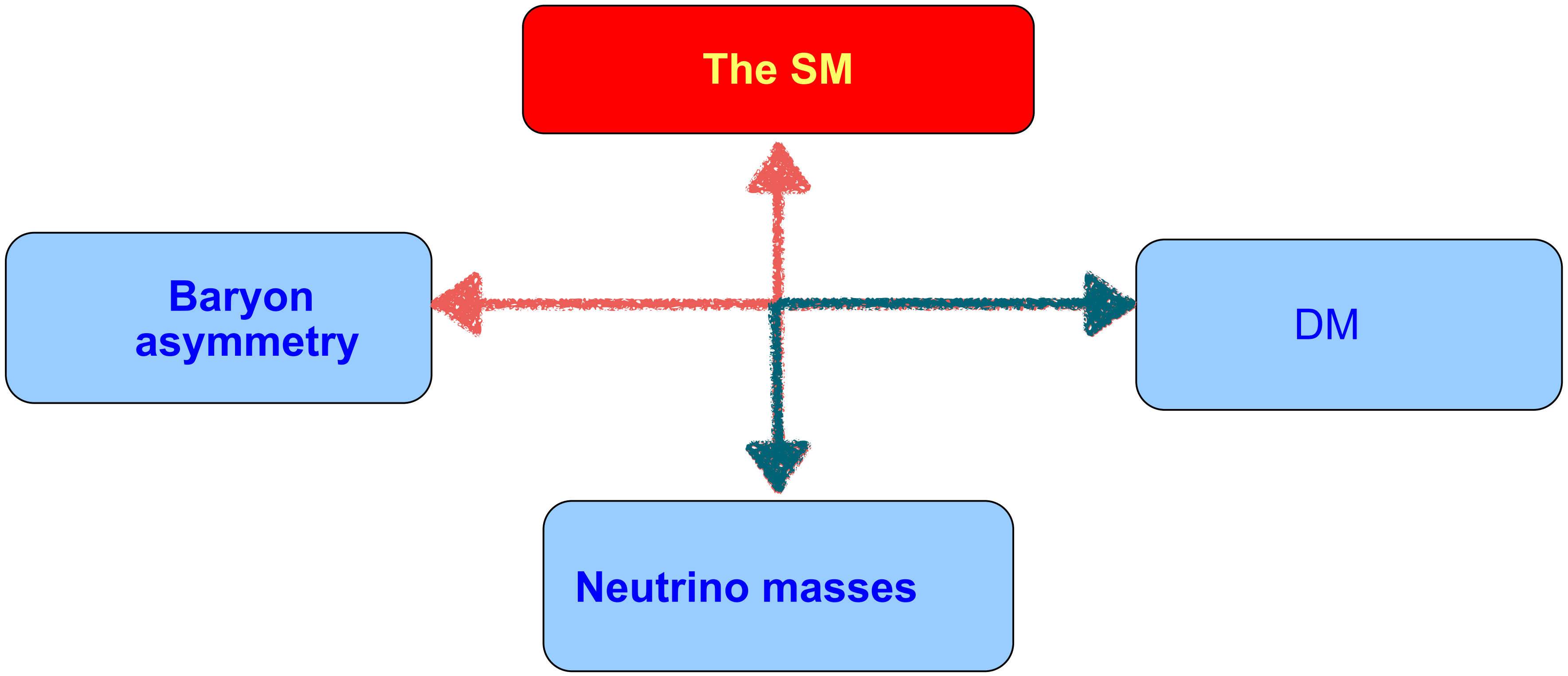
How to connect neutrino physics with DM?

The SM

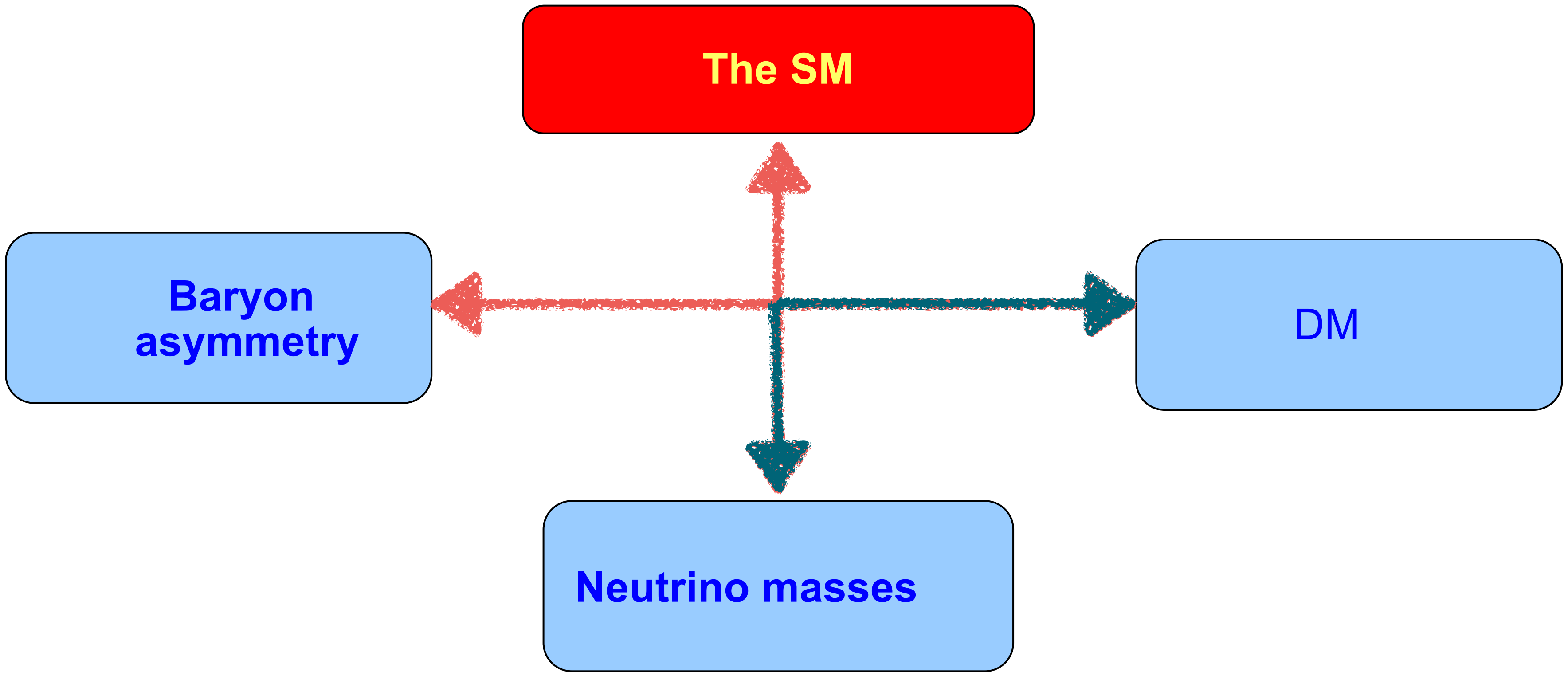
How to connect neutrino physics with DM?



How to connect neutrino physics with DM?



How to connect neutrino physics with DM?



Majoron

Inert+loops

DDM

loops with higher Higgs representations

KeV sterile neutrinos

etc...

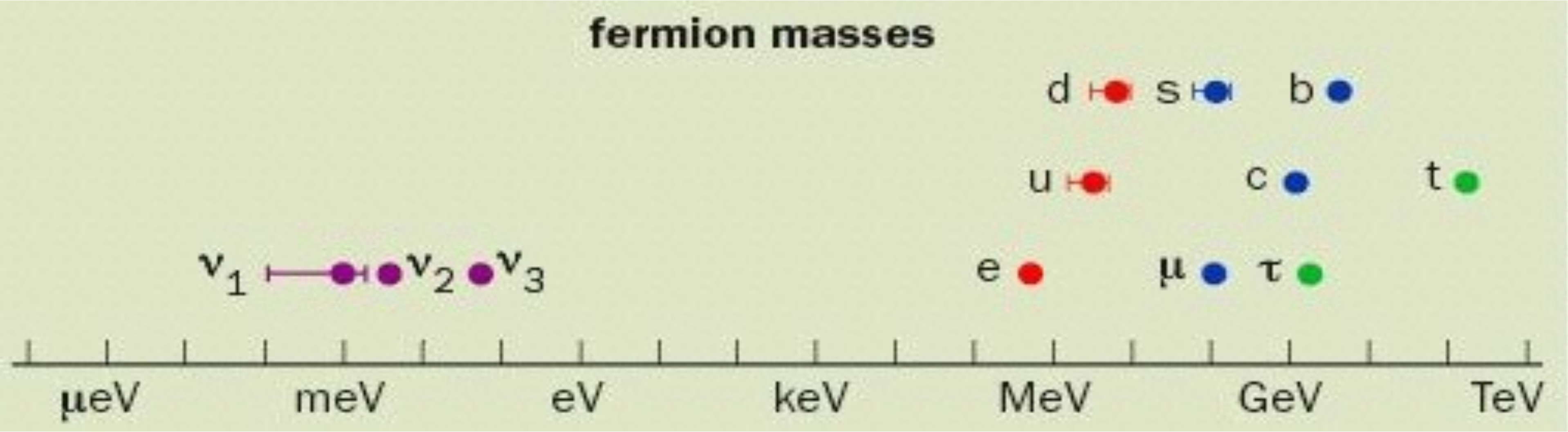
If Dirac

Can be either

If Dirac

Can be either

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



- many orders of magnitude

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

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

The Yukawa couplings are very different

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

Majorana Neutrinos

If we allow L to be violated?

Majorana Neutrinos

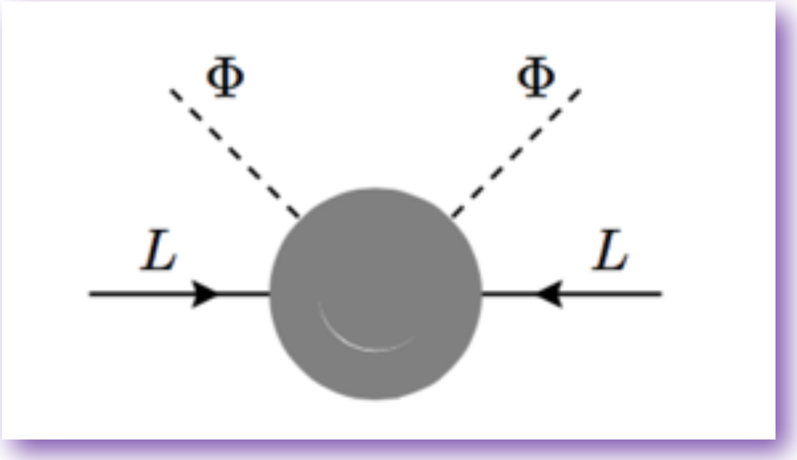
If we allow L to be violated?

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

Majorana Neutrinos

If we allow L to be violated?

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



Weinberg, S. (1980)

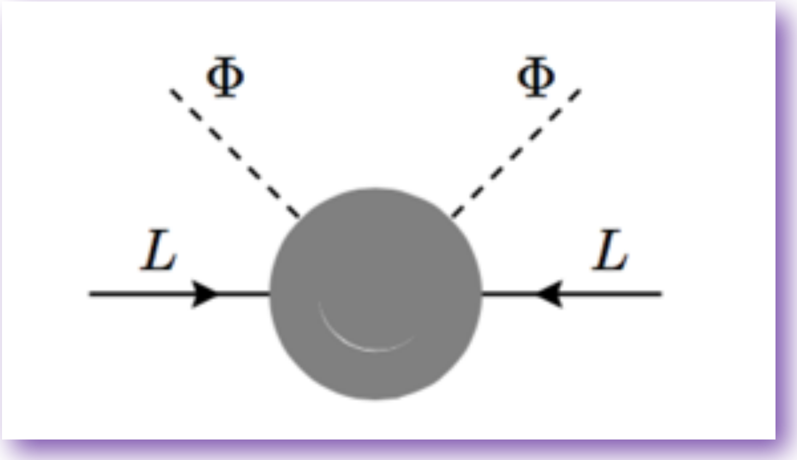
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5$$

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

Majorana Neutrinos

If we allow L to be violated?

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



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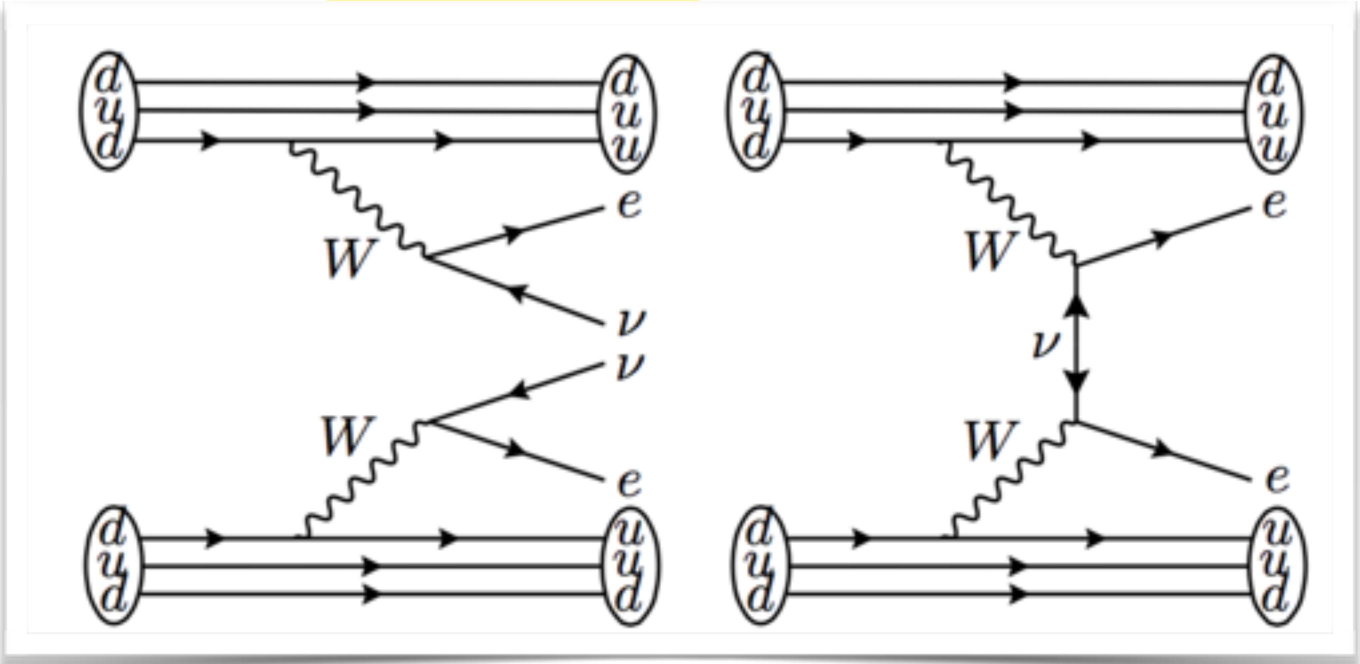
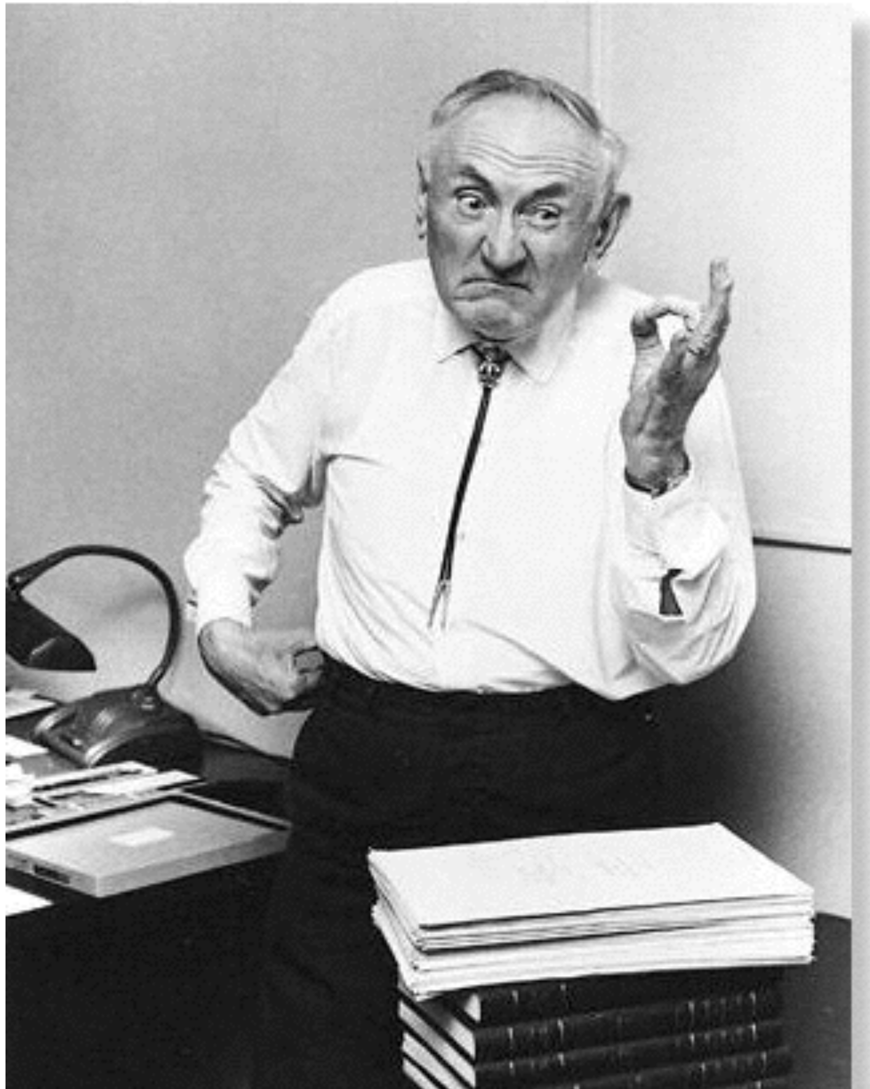
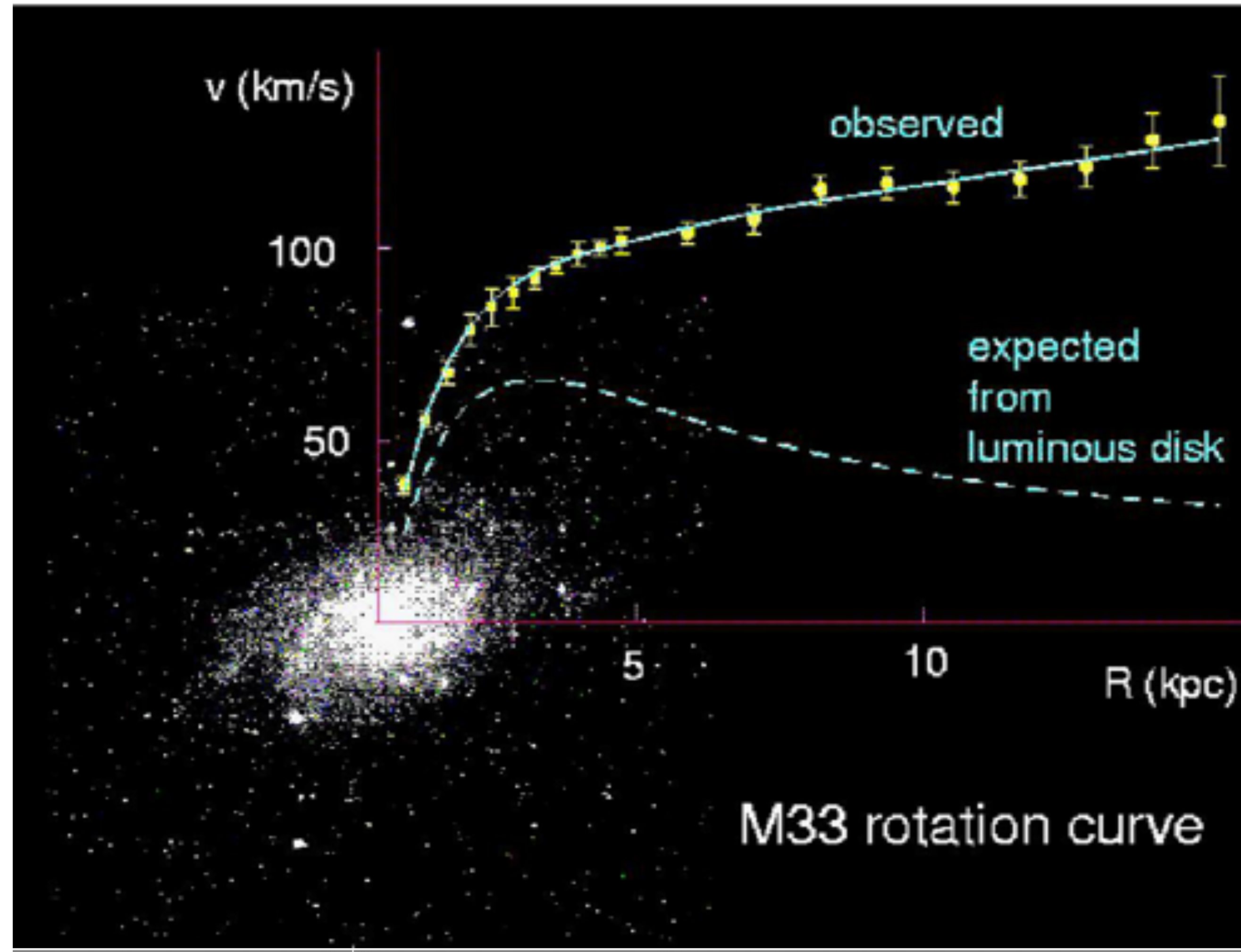
- Implications?

$0\nu\beta\beta$





Zwicky 1933



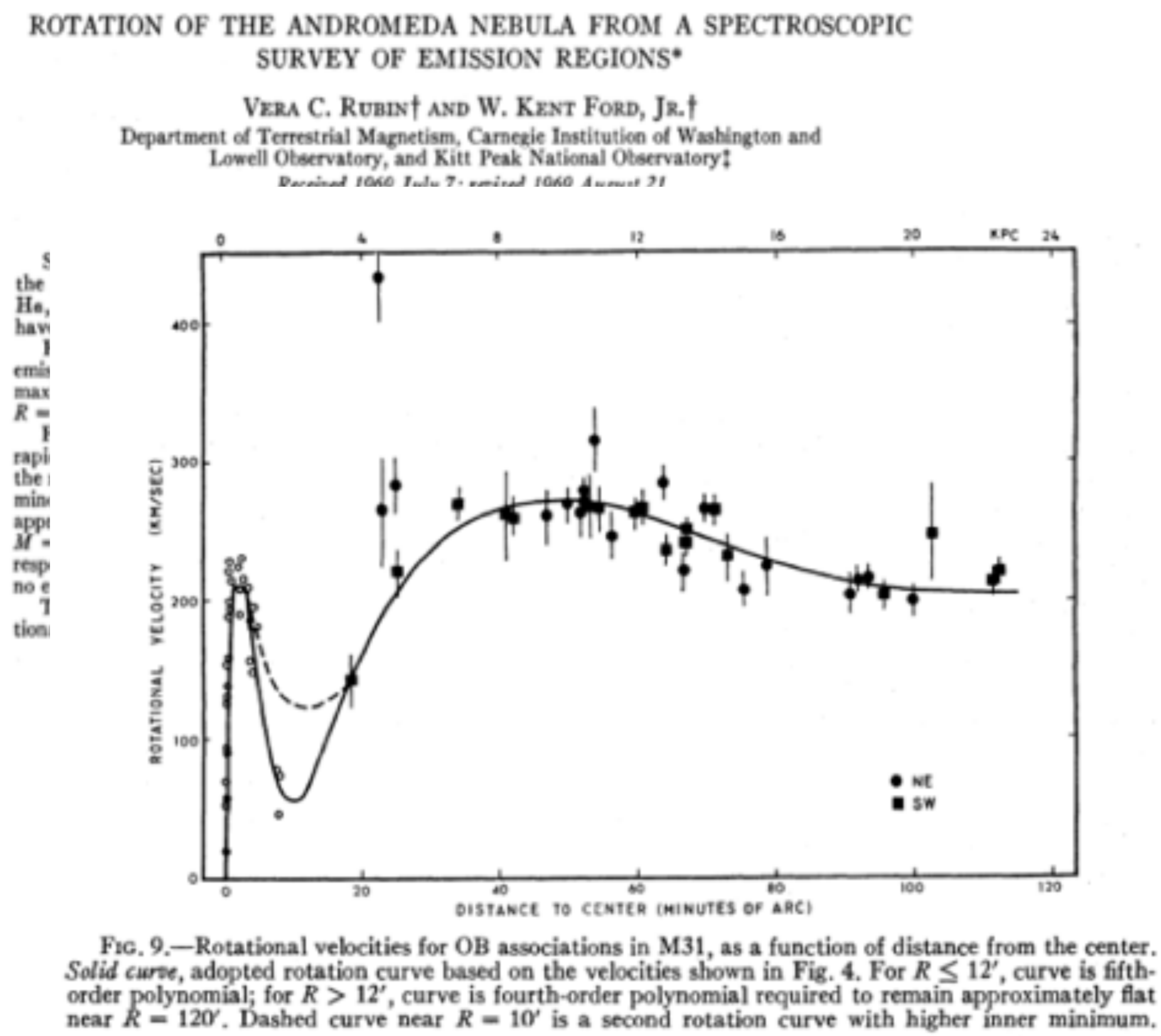
Dark Matter

DM evidence

Not only in the clusters of galaxies

Vera Rubin
70's

Velocidad de las estrellas
en la galaxia andromeda



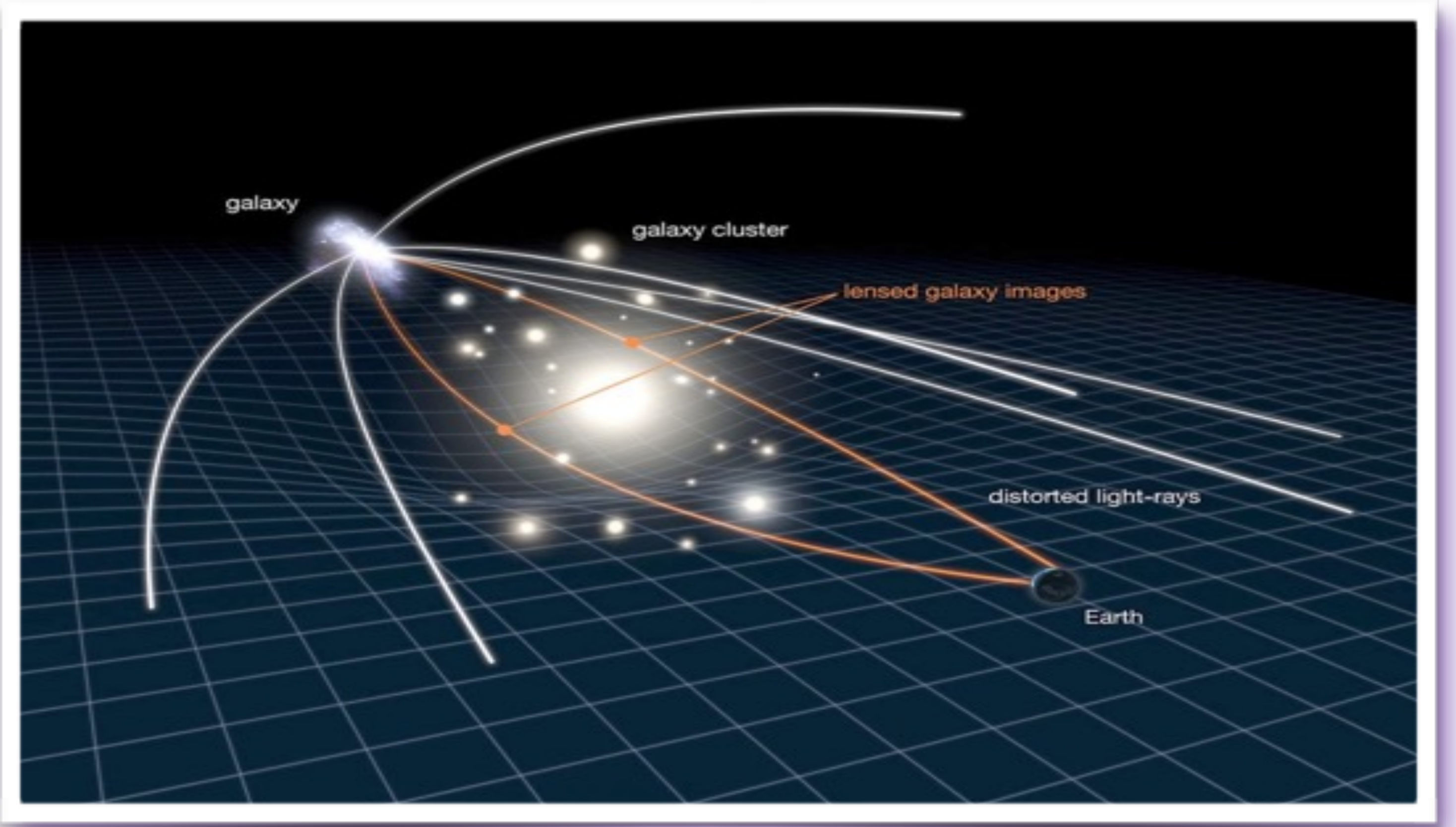
ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†

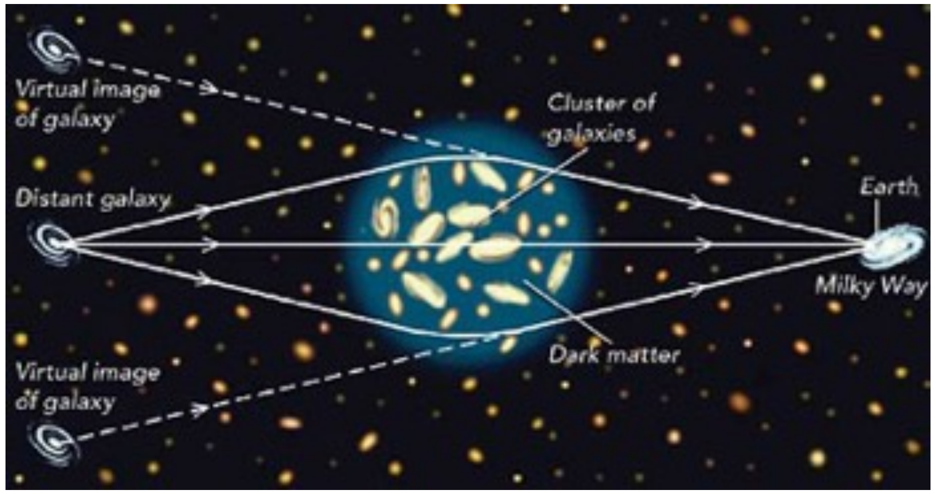
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

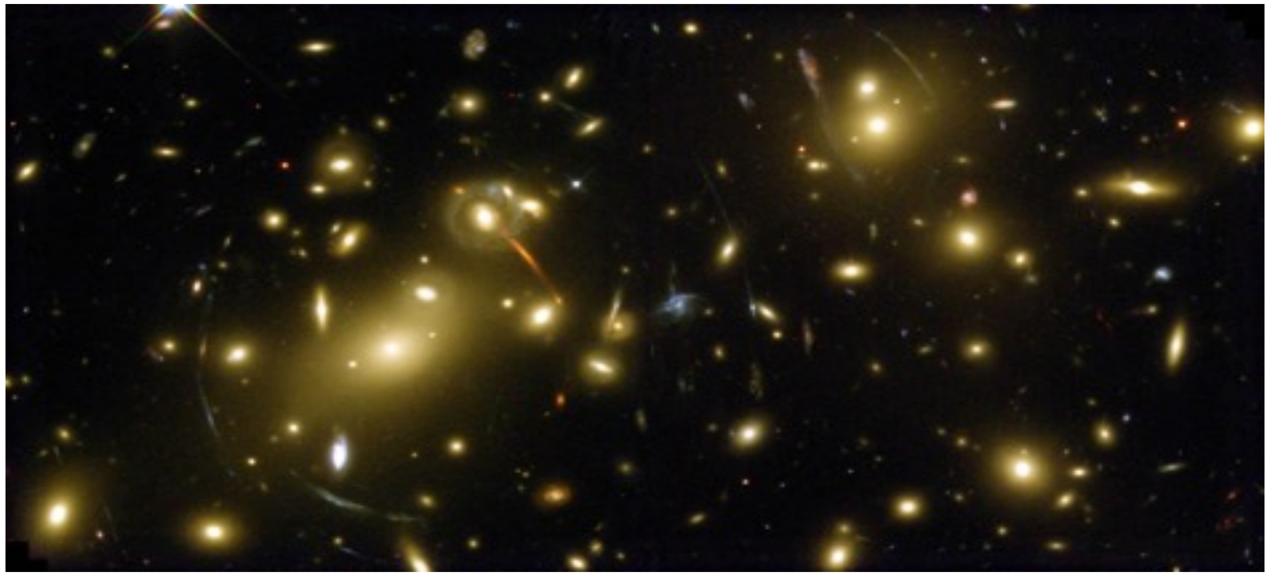
FIG. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. *Solid curve*, adopted rotation curve based on the velocities shown in Fig. 4. For $R \leq 12'$, curve is fifth-order polynomial; for $R > 12'$, curve is fourth-order polynomial required to remain approximately flat near $R = 120'$. Dashed curve near $R = 10'$ is a second rotation curve with higher inner minimum.

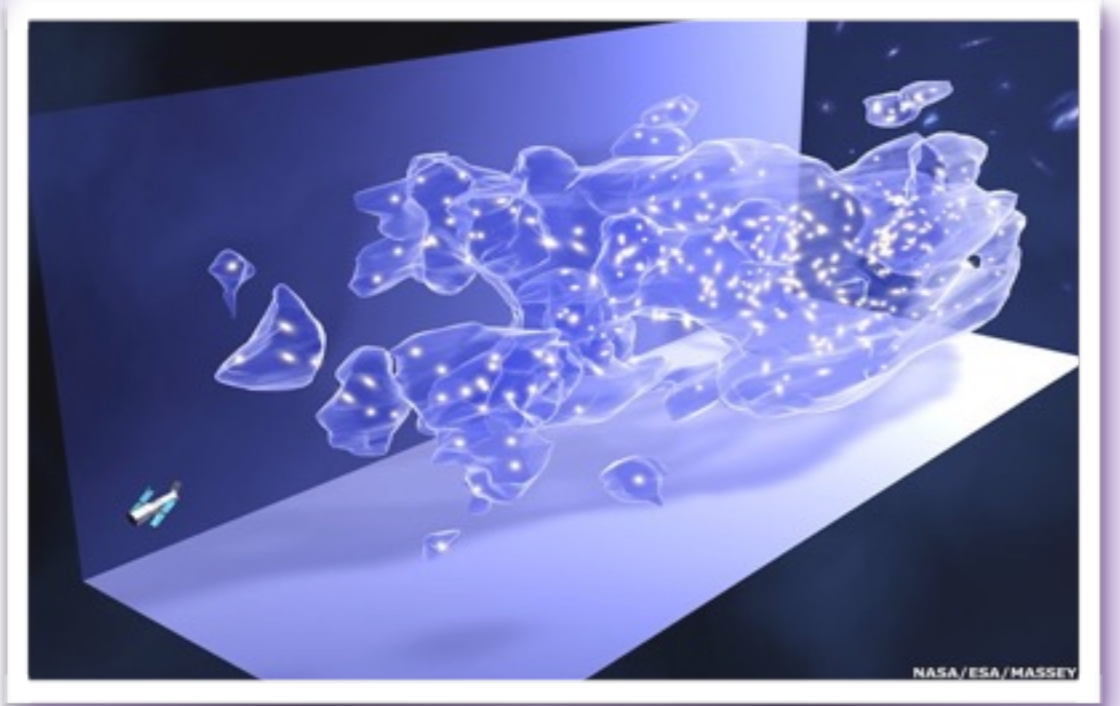
DM evidence



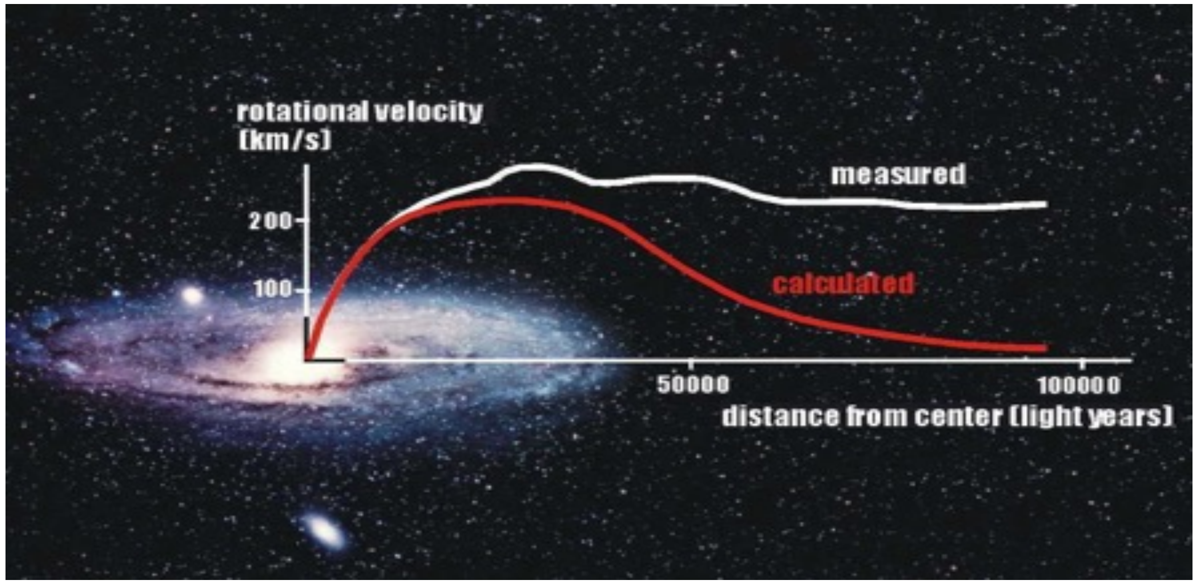
Gravitational lensing

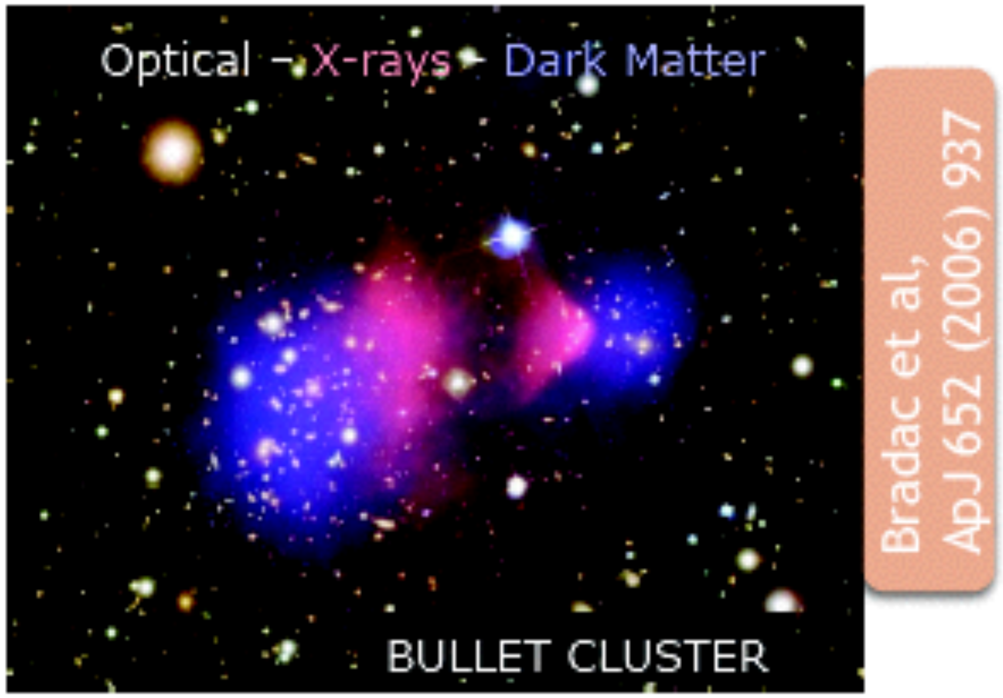


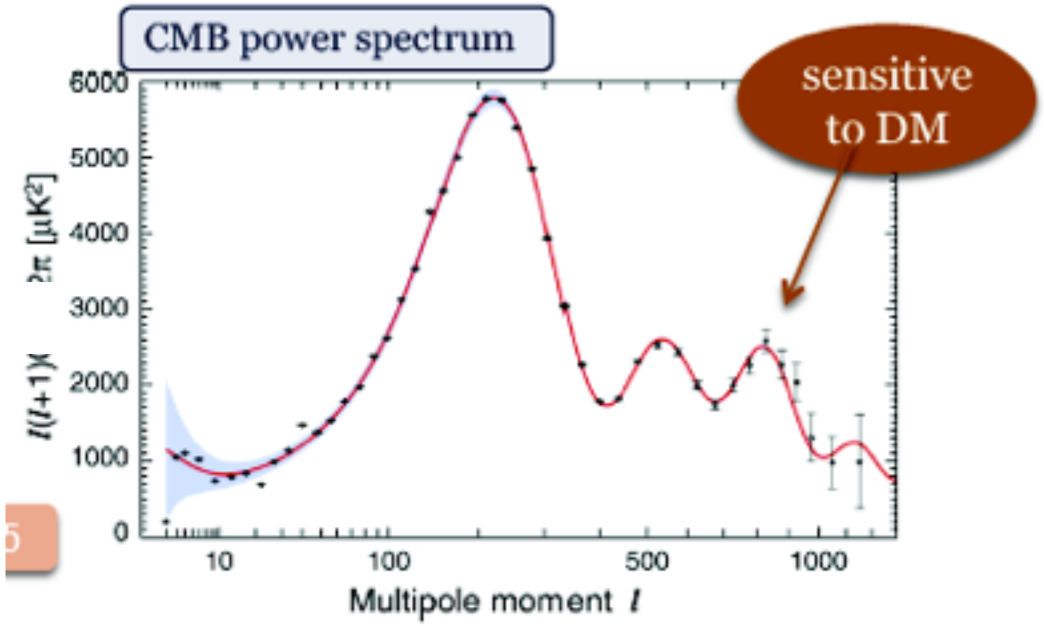




- Rotational curves
- Clusters of galaxies
- CMB anisotropies
- BBN
- ...

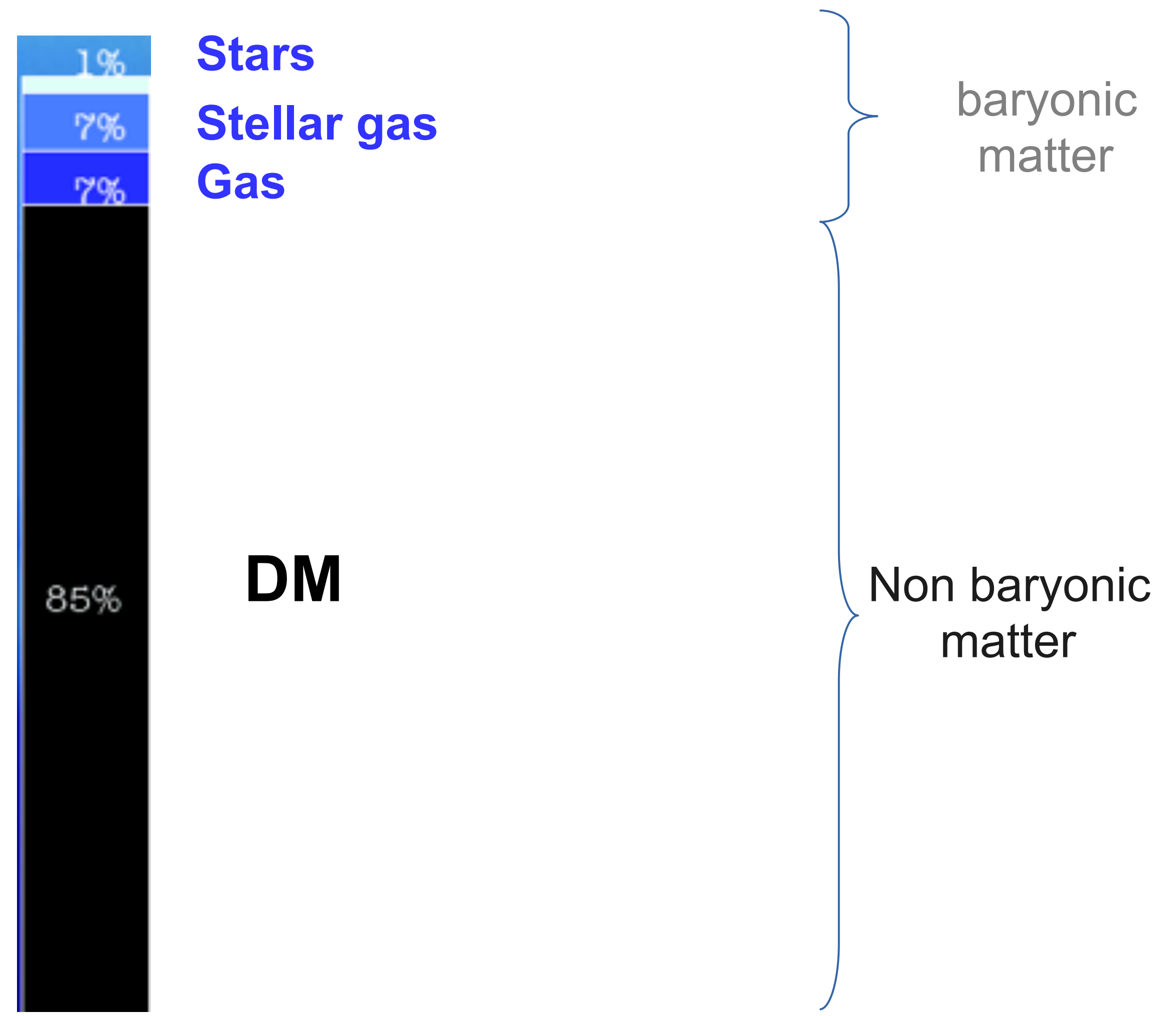






See one of Eric's Talks

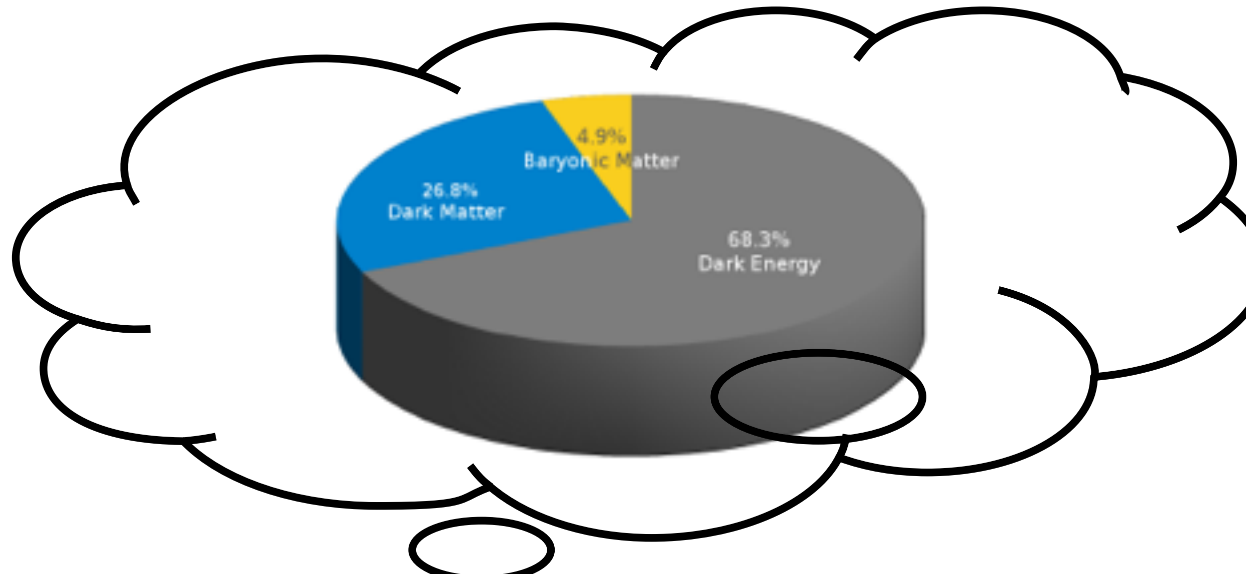
Inventary of matter in the universe



What do we “know” about DM?

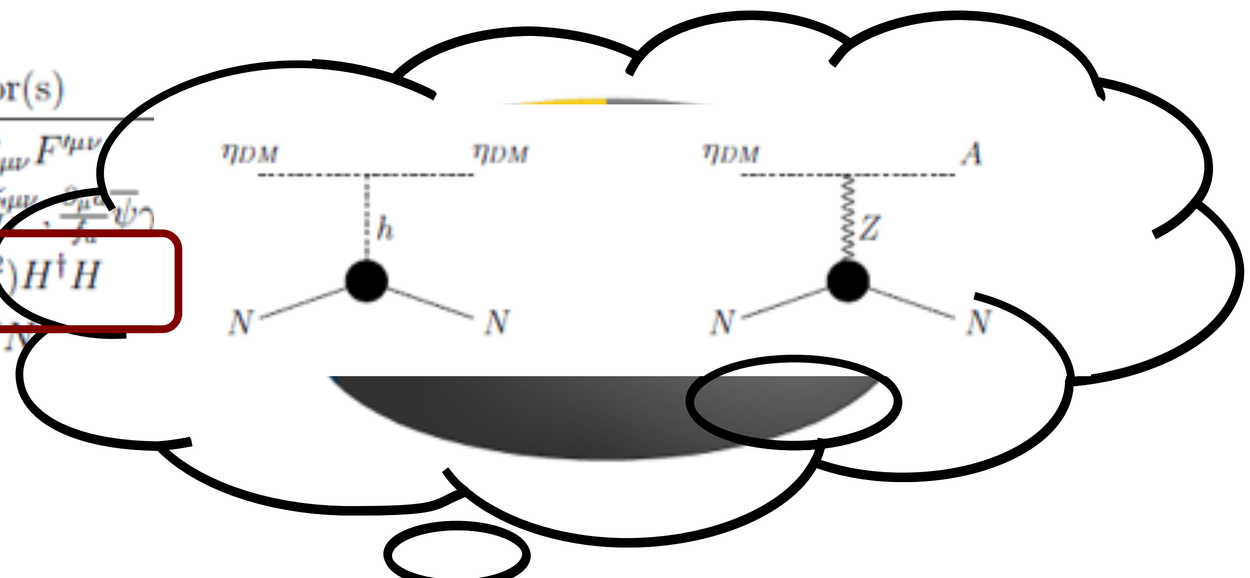
- Long lived (Stable)
- DM cosmological abundance extracted from observations
- DM is cold (or warm)
- Electrically neutral
- DM-DM and DM-SM interactions constrained by observations

DM puzzle



DM puzzle

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

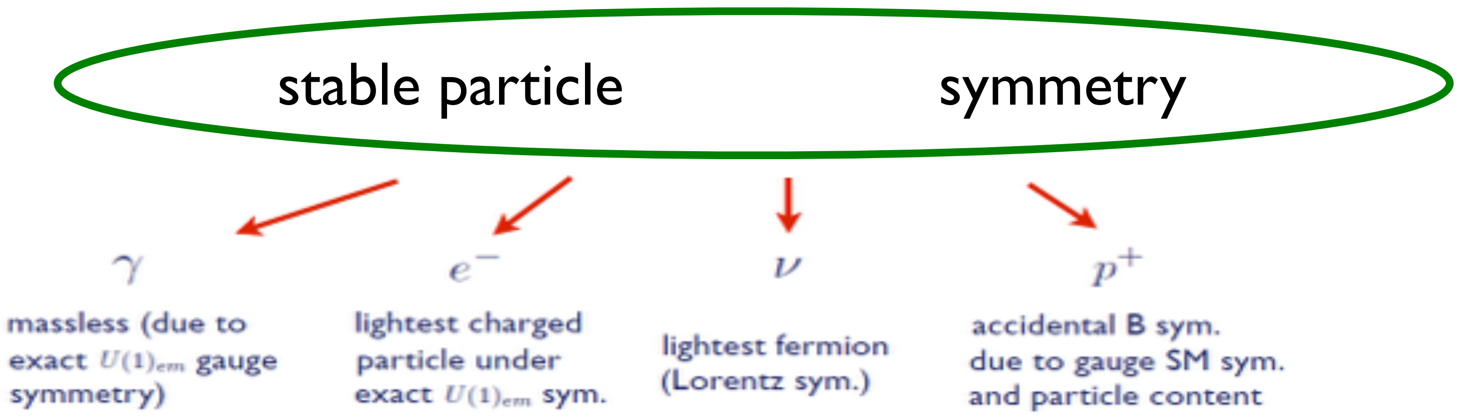


Higgs Portal

Direct detection

One simple Idea for DM

Inert scalar DM



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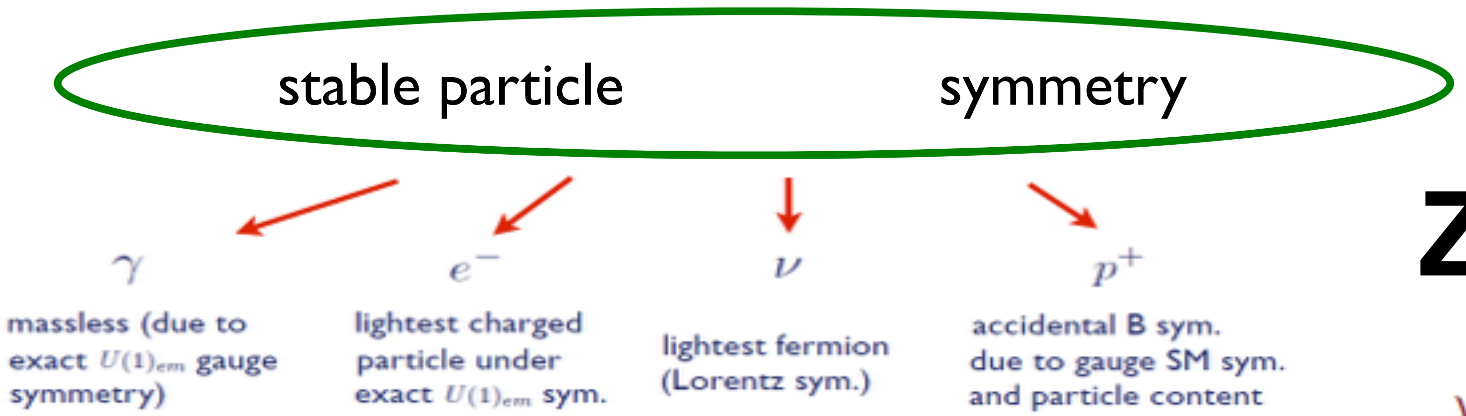
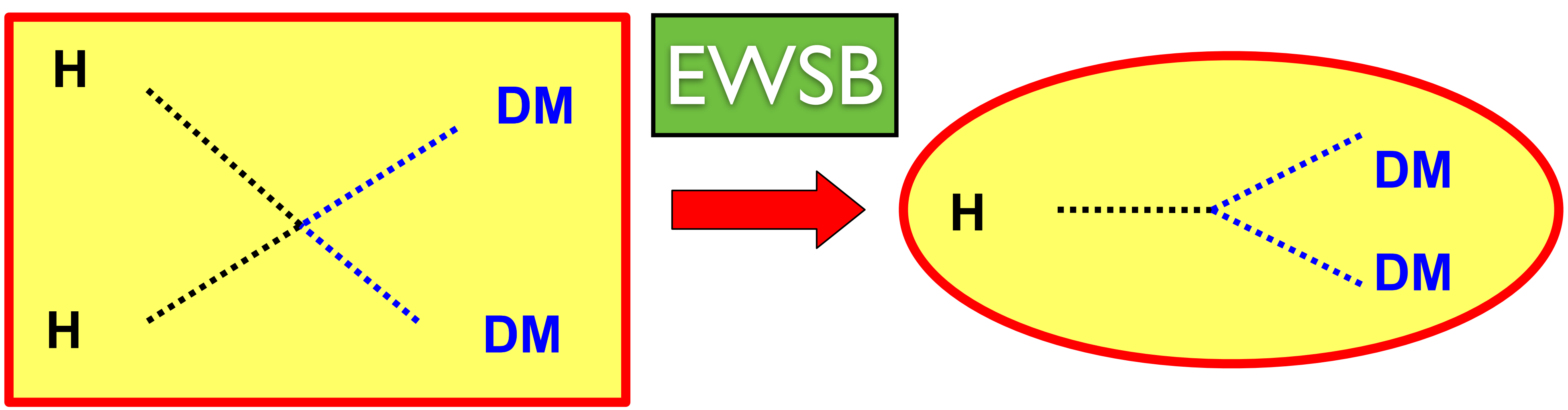


Deshpande and Ma (1978)

SM + scalar

Z_2	+	-

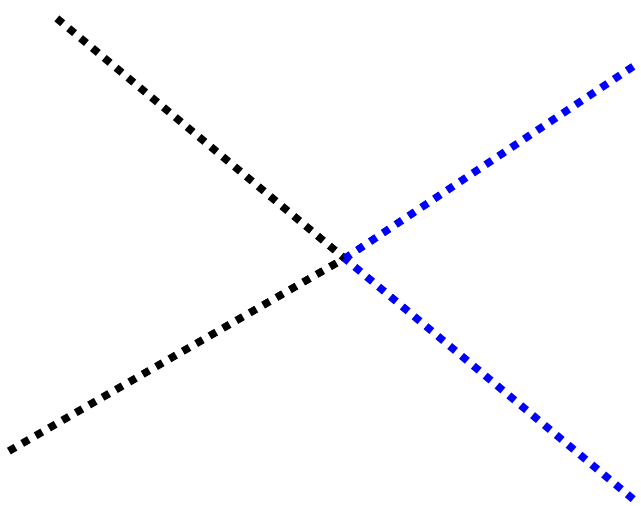
$$\lambda_3|H_1|^2|H_2|^2+\lambda_4|H_1^\dagger H_2|^2+\frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2+h.c.\right]$$



Higgs portal

Neutrino masses in the Inert DM?

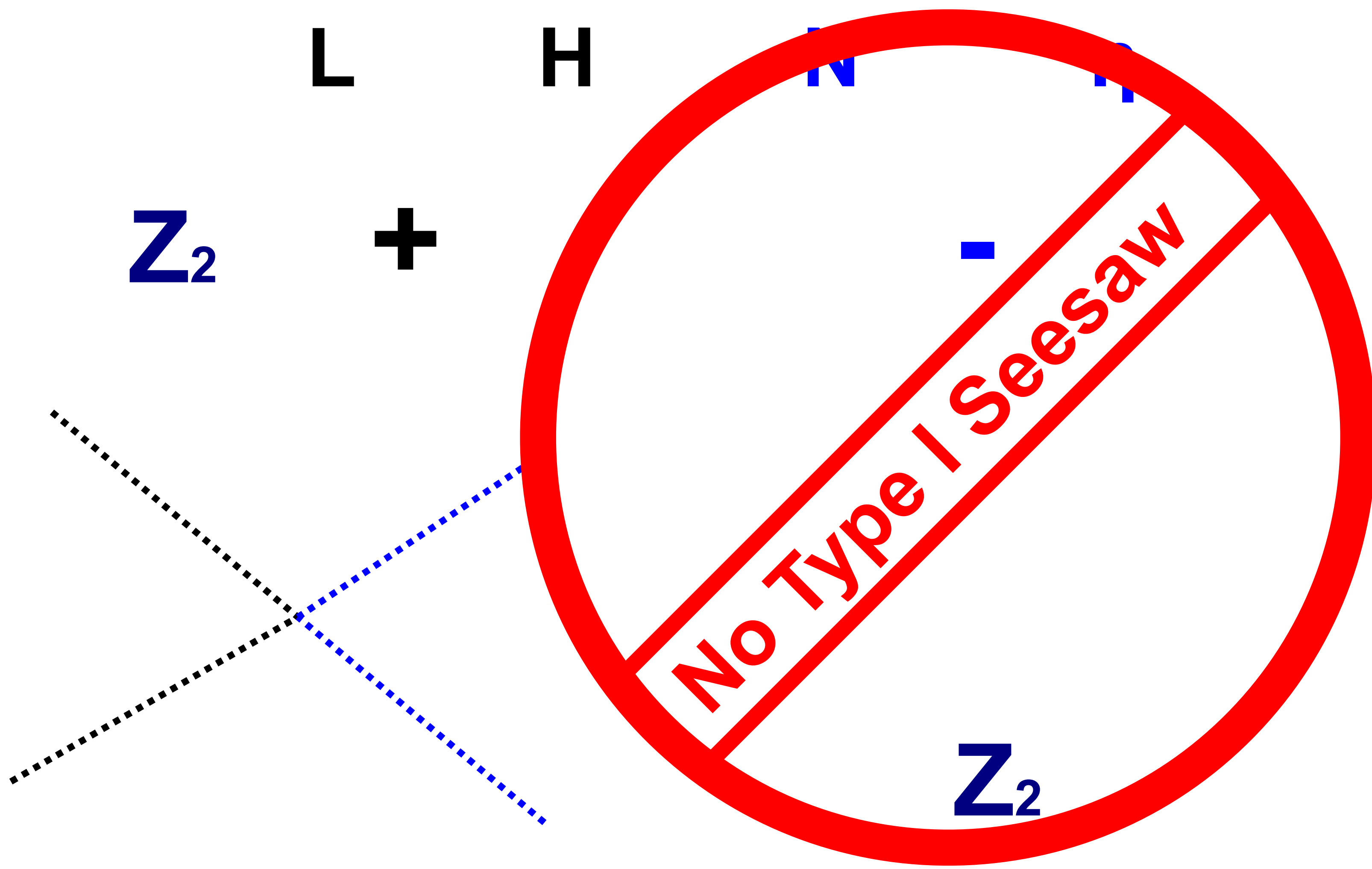
	L	H	N	η
Z_2	+		-	



Z_2

$\langle \eta \rangle = 0 \Rightarrow m_D = 0$

Neutrino masses in the Inert DM?



$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

$\langle \eta \rangle = 0$ → $m_D = 0$

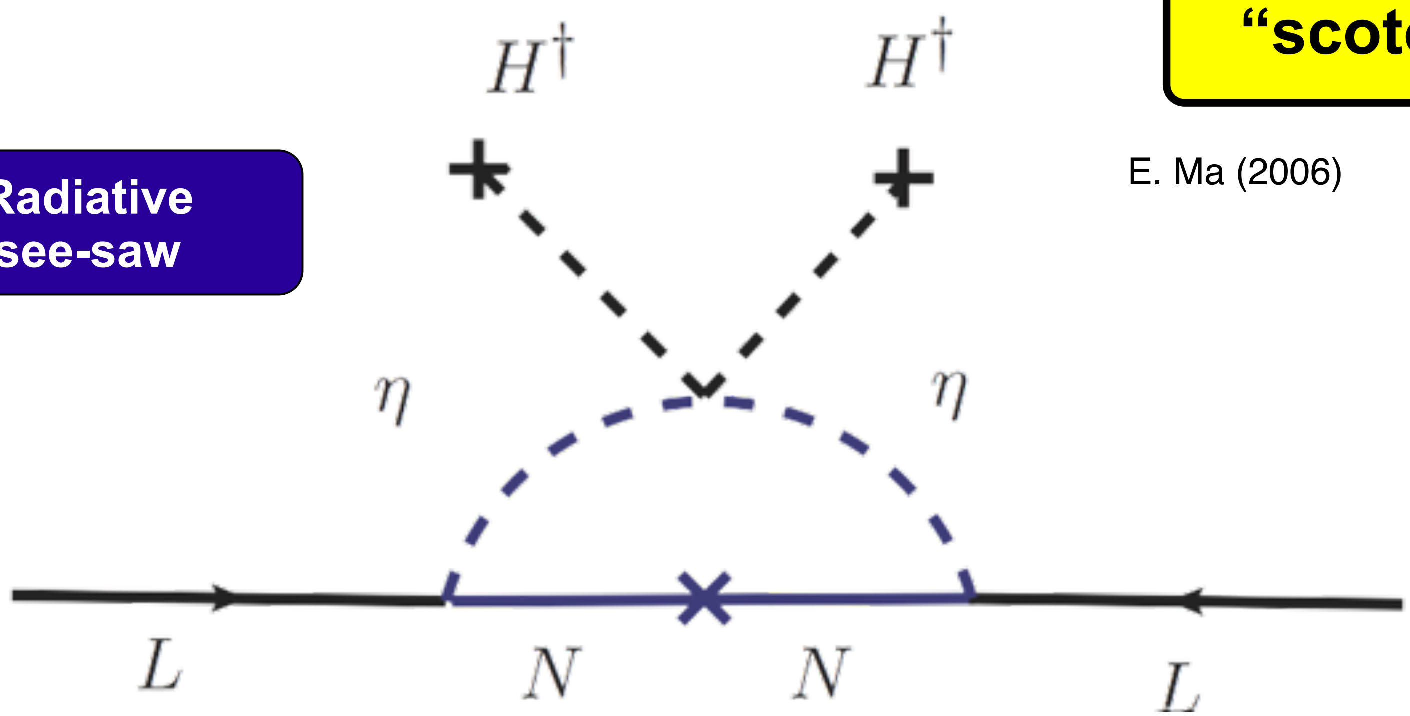
Neutrino masses in the inert DM

A. Zee (1980)

"scotogenic"

E. Ma (2006)

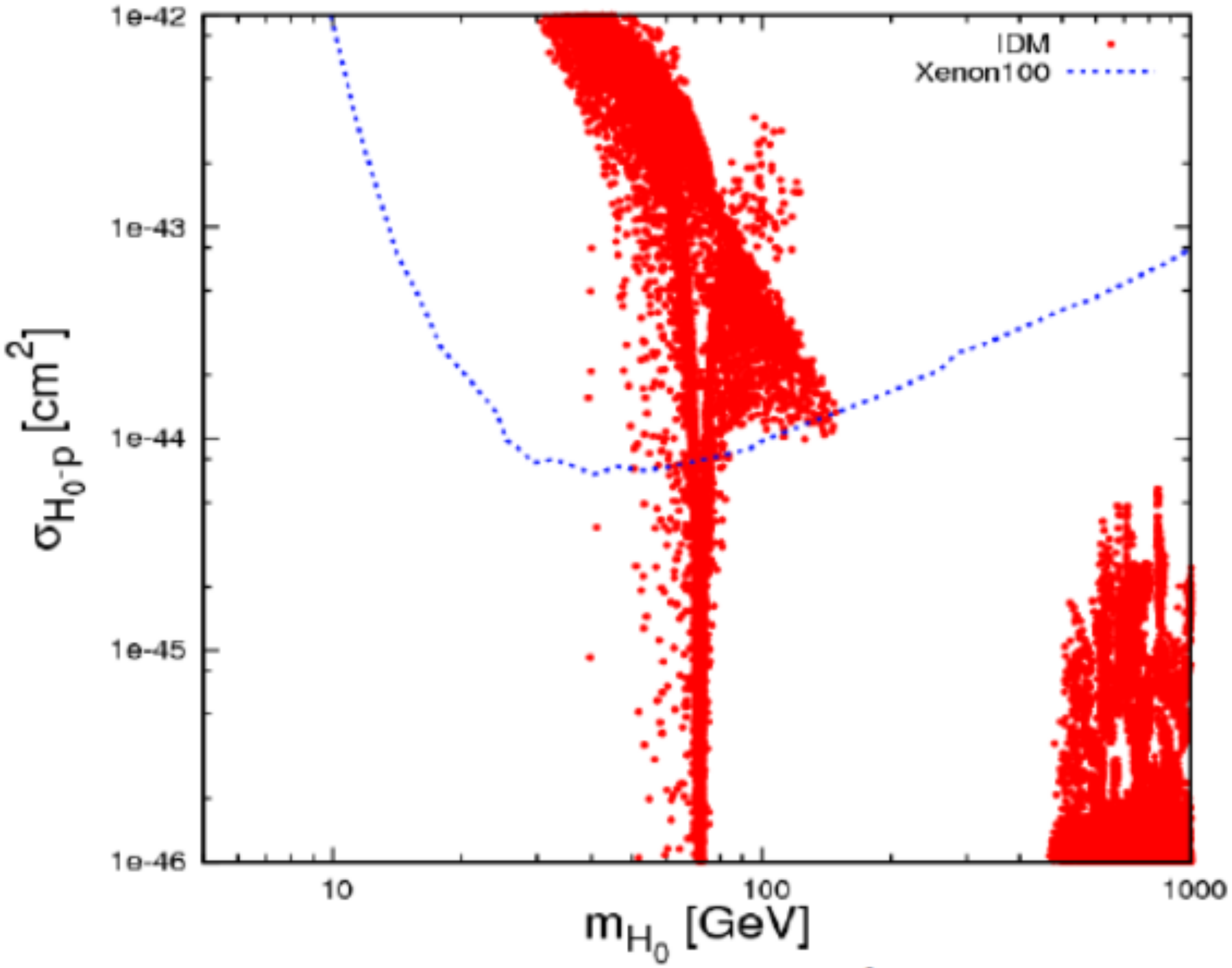
Radiative see-saw



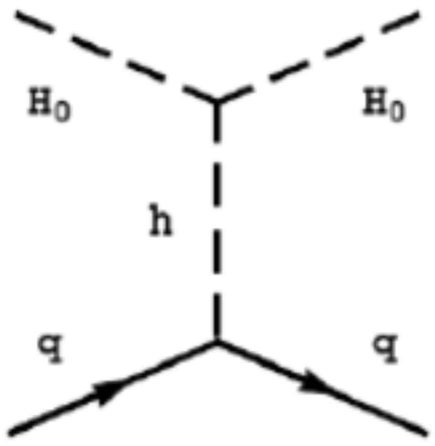
If $M_k^2 >> m_0^2$, then

$$(\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2} \sum_k \frac{h_{ik} h_{jk}}{M_k} \left[\ln \frac{M_k^2}{m_0^2} - 1 \right]$$

Direct Detection



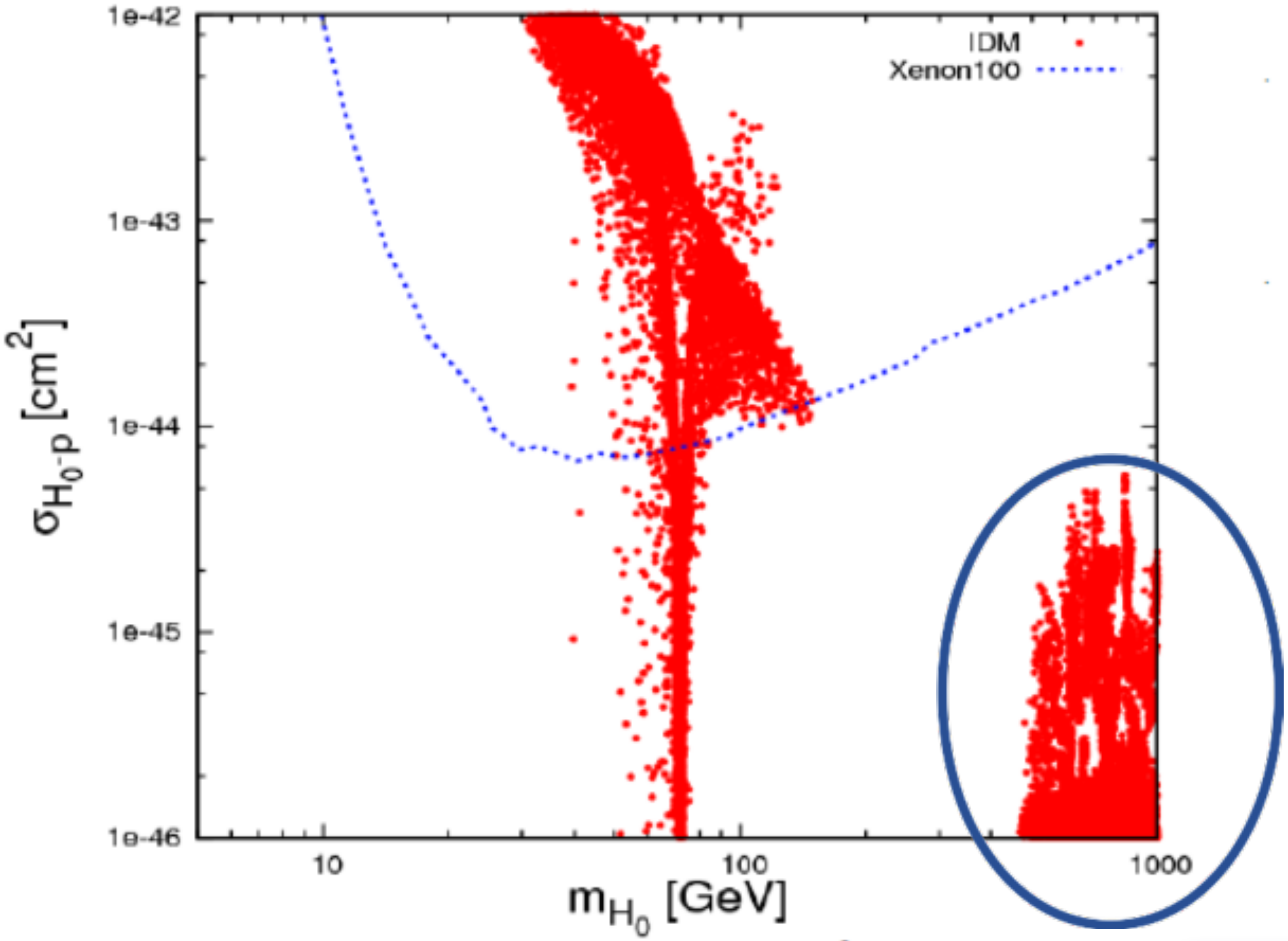
result of a scan giving rise to $0.09 < \Omega_{H_0} h^2 < 0.13$



$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2} \right)^2$$

Laura Lopez-Honorez

Direct Detection



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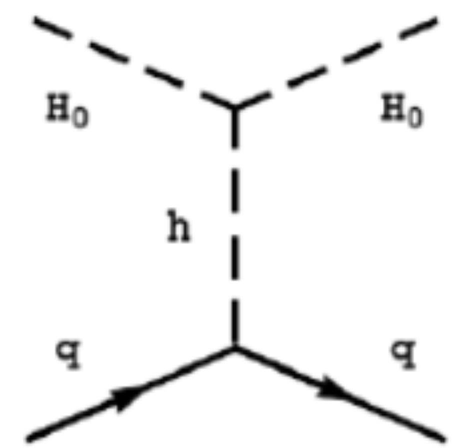


$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2} \right)^2$$

High mass regime

Laura Lopez-Honorez

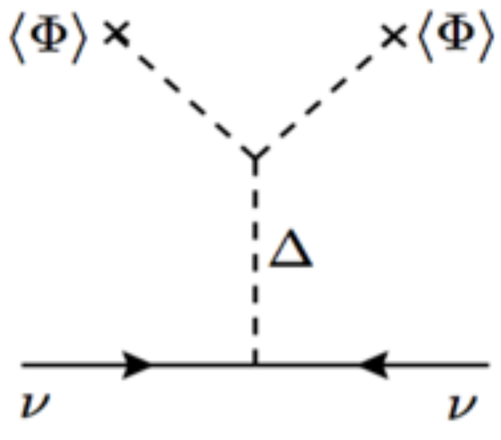
Other Possibilities

with higher representations

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

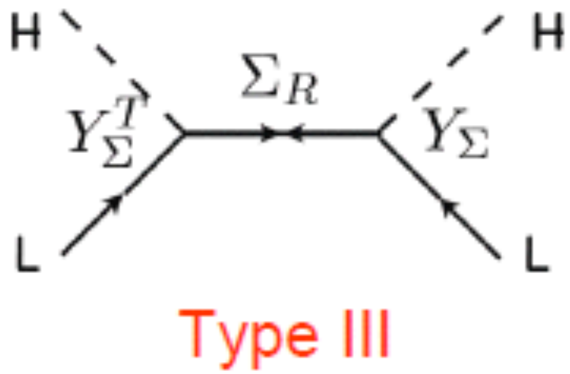
type II seesaw

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



type III seesaw

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



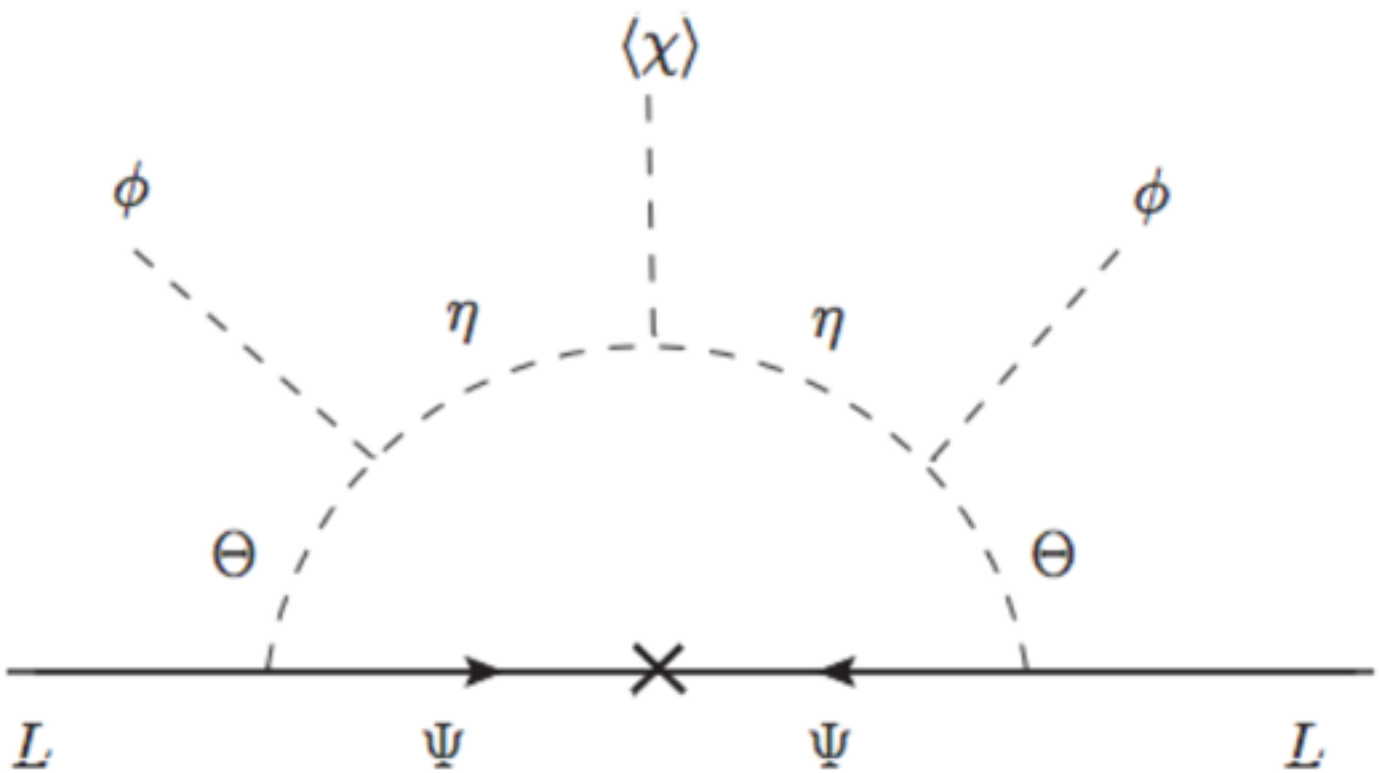
Neutrino masses from higher dim Higgses

Aranda, EP (2015)

- Imposing the condition rho parameter 1 at tree level

$$\rho = \frac{\Sigma_\phi \left[\, j_\phi(j_\phi + 1) - Y_\phi^2 \,\right] v_\phi^2}{\Sigma_\phi \, 2Y_\phi^2 \, v_\phi^2}$$

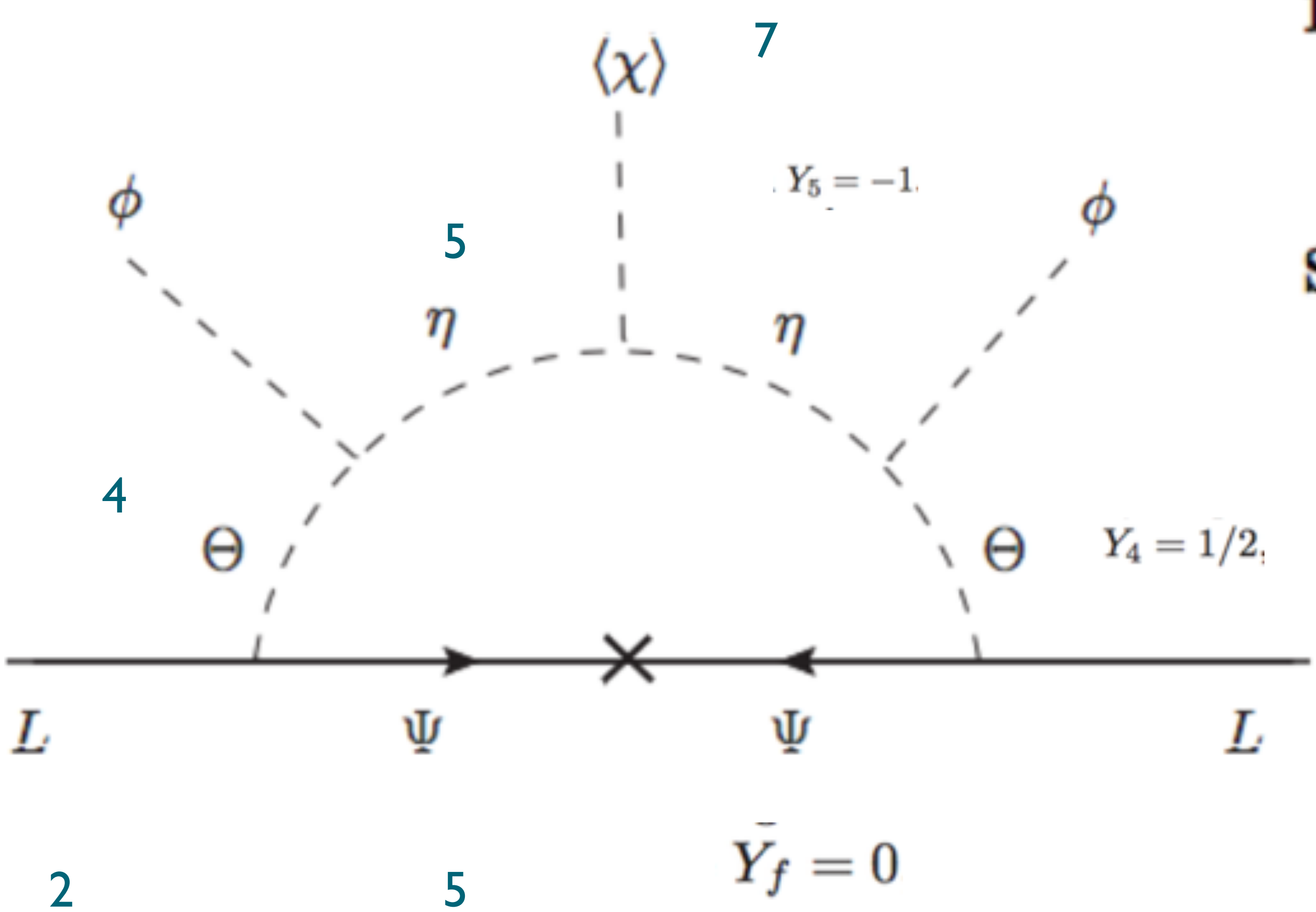
- the minimal is a septet with Y=2
- What do we need for this to contribute to Neutrino masses?
- What are the conditions?



2×2	$=$	$1 + 3$
3×2	$=$	$2 + 4$
3×3	$=$	$1 + 3 + 5$
4×2	$=$	$3 + 5$
4×3	$=$	$2 + 4 + 6$
4×4	$=$	$1 + 3 + 5 + 7$
5×2	$=$	$4 + 6$
5×3	$=$	$3 + 5 + 7$
5×4	$=$	$2 + 4 + 6 + 8$
5×5	$=$	$1 + 3 + 5 + 7 + 9$
6×2	$=$	$5 + 7$
6×3	$=$	$4 + 6 + 8$
6×4	$=$	$3 + 5 + 7 + 9$
6×5	$=$	$2 + 4 + 6 + 8 + 10$
6×6	$=$	$1 + 3 + 5 + 7 + 9 + 11$
7×2	$=$	$6 + 8$
7×3	$=$	$5 + 7 + 9$
7×4	$=$	$4 + 6 + 8 + 10$
7×5	$=$	$3 + 5 + 7 + 9 + 11$
7×6	$=$	$2 + 4 + 6 + 8 + 10 + 12$
7×7	$=$	$1 + 3 + 5 + 7 + 9 + 11 + 13$

How to generate neutrino masses?

Aranda, EP (2015)



fermionic SU(2) 5-plet Ψ

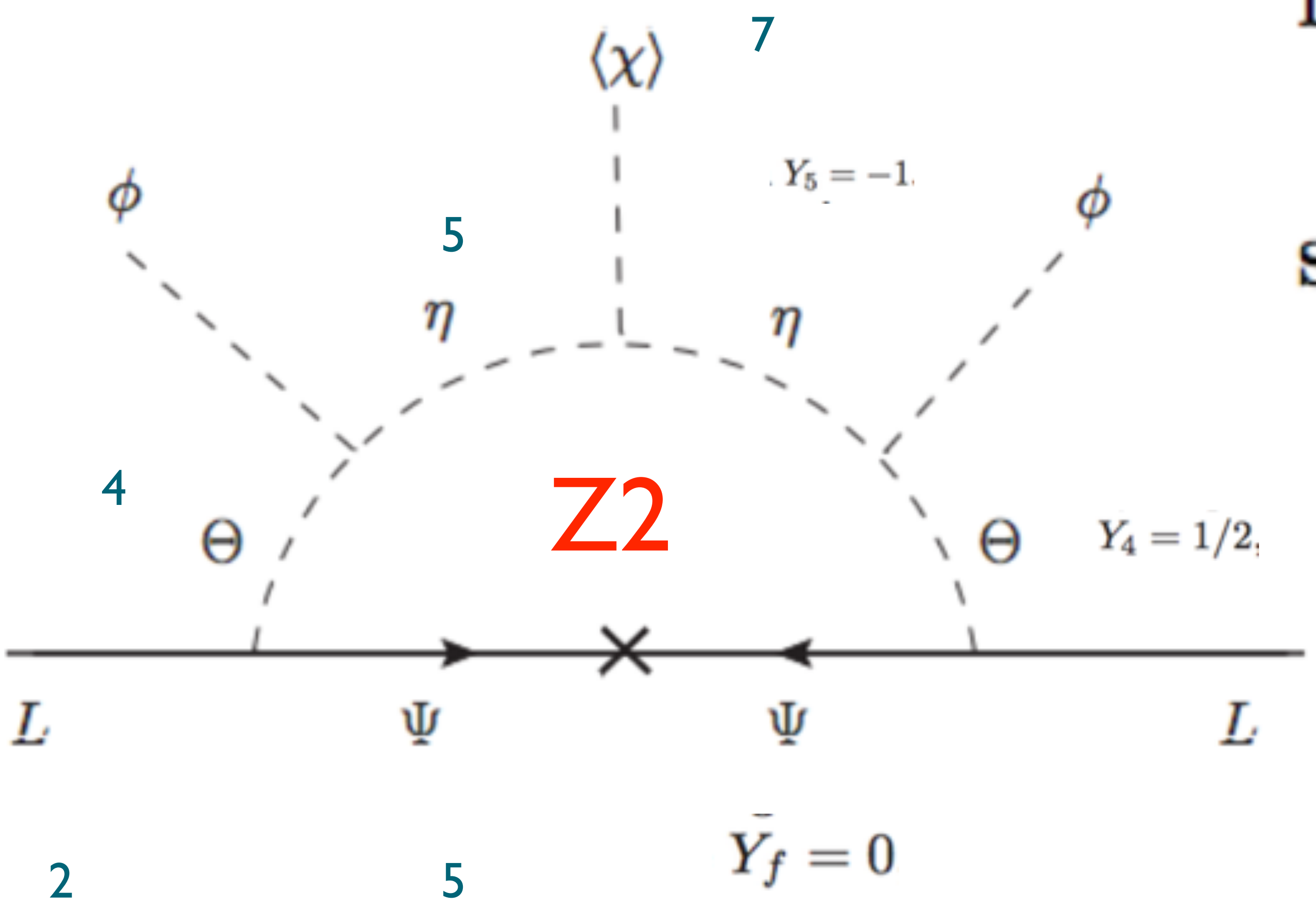
scalars in the quartet (Θ)

and quintet (η)

$LL\phi\phi\widetilde{\chi}$

How to generate neutrino masses?

Aranda, EP (2015)



fermionic SU(2) 5-plet Ψ

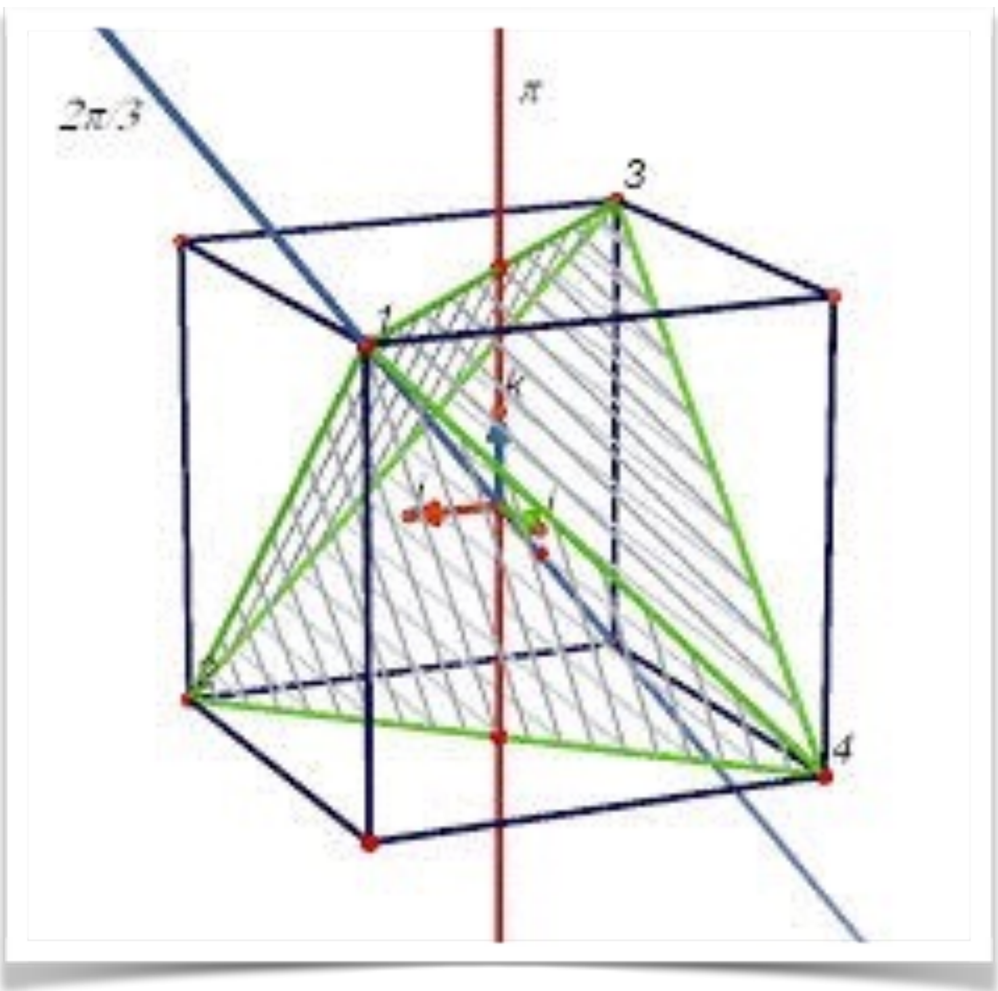
scalars in the quartet (Θ)

and quintet (η)

$LL\phi\phi\tilde{\chi}$

In order to preserve the tree level rho parameter we must impose a Z2 symmetry, in such a way the neutral components of the scalar fields remain vevless

Discrete Dark Matter Introduction



A_4 even permutations
4 objects

A flavor group
Non-Abelian

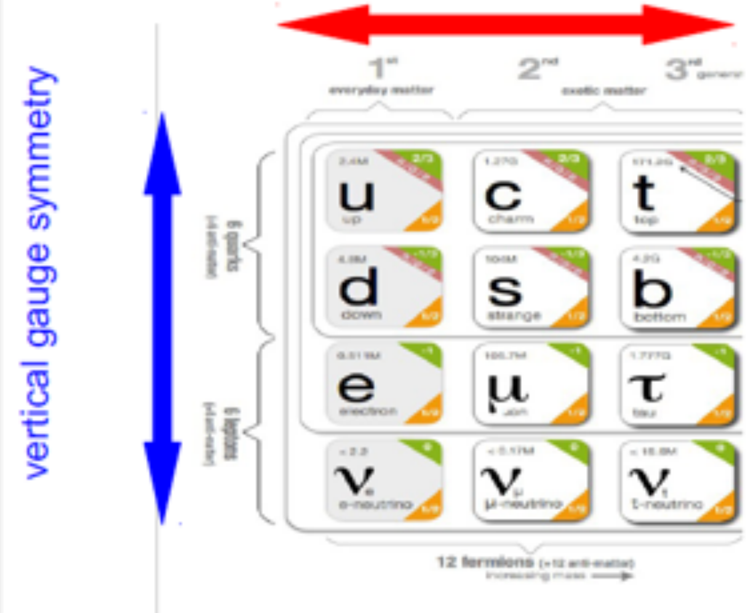
Very popular because it was useful
reproduce the TBM mixing

Babu-Ma-Valle
and
Altarelli-Feruglio

Frampton and Kephart, PRD64 (01)

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

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



Abelian, non-abelian
continuous, discrete,
global, local

Flavor Symmetries (Horizontal)

An example: A4

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

The generators are :

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

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

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

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

Z_2 $\qquad Z_3$

A4 and TBM

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

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

Z_3

Altarelli Feruglio (2005)

Z_2

$$m = \begin{pmatrix} x & y & y \\ y & x+v & y-v \\ y & y-v & x+v \end{pmatrix}$$

M_l

M_ν

A4 completely broken

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

Large neutrino mixing

$\Longleftrightarrow$

$\phi \neq \phi'$

Misalignment

We have symmetries (stability)?

Z3 in the charged sector

Z2 in the neutrino sector

TBM

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

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Z3 in the charged sector X

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stabilize the DM

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Z2 in the charged sector

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1, 1', 1''

3

The simplest model

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

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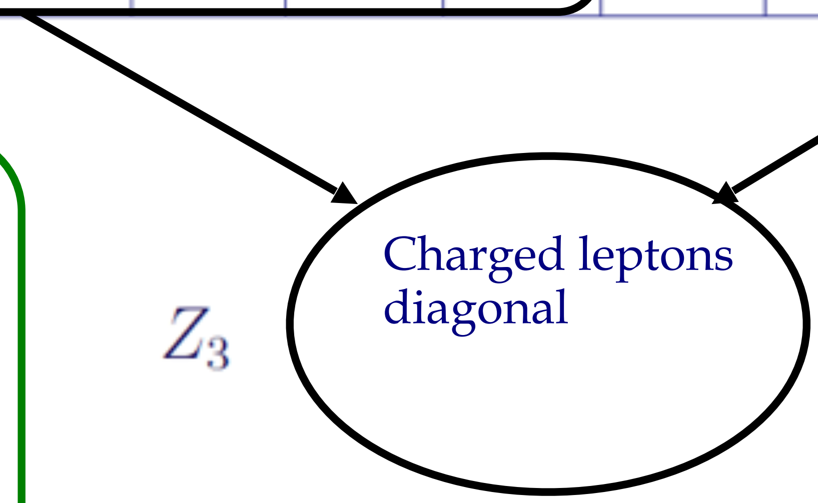
	L_e	L_μ	L_τ	l^c_e	l^c_μ	l^c_τ	N_T	N_4	H	η
$SU(2)$	2	2	2	1	1	1	1	1	2	2
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1	1	3



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

Z_3

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

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

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

$\langle H^0 \rangle = v_h$

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

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

Neutrino masses in the model

Scaling matrix,
Rodejohan and Mohapatra

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

Inverse mass Hierarchy

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

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$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34±0.20	1.95–2.74	1.77–2.94

Inverse mass Hierarchy

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

Reactor mixing angle?

	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

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

The A4 breaking

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

η

ϕ (1,0,0)

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

Two zero-textures B3

Frampton, Glashow, Marfatia
Phys.Lett. B536 (2002) 79-82

Merle, Rodejohann
Phys.Rev. D73 (2006) 073012

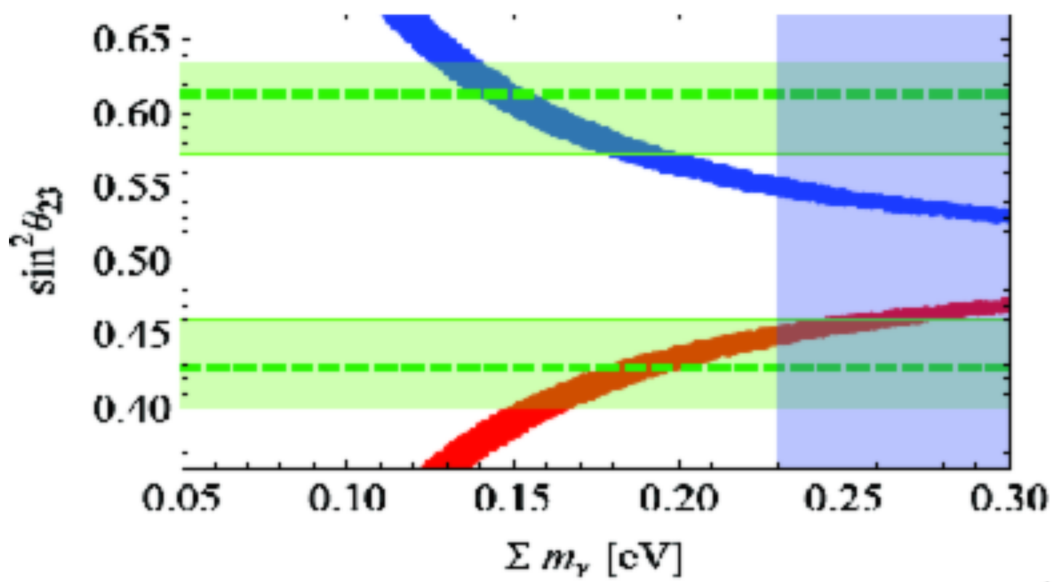
Ludl, Morisi, EP
Nucl.Phys. B857 (2012) 411-423

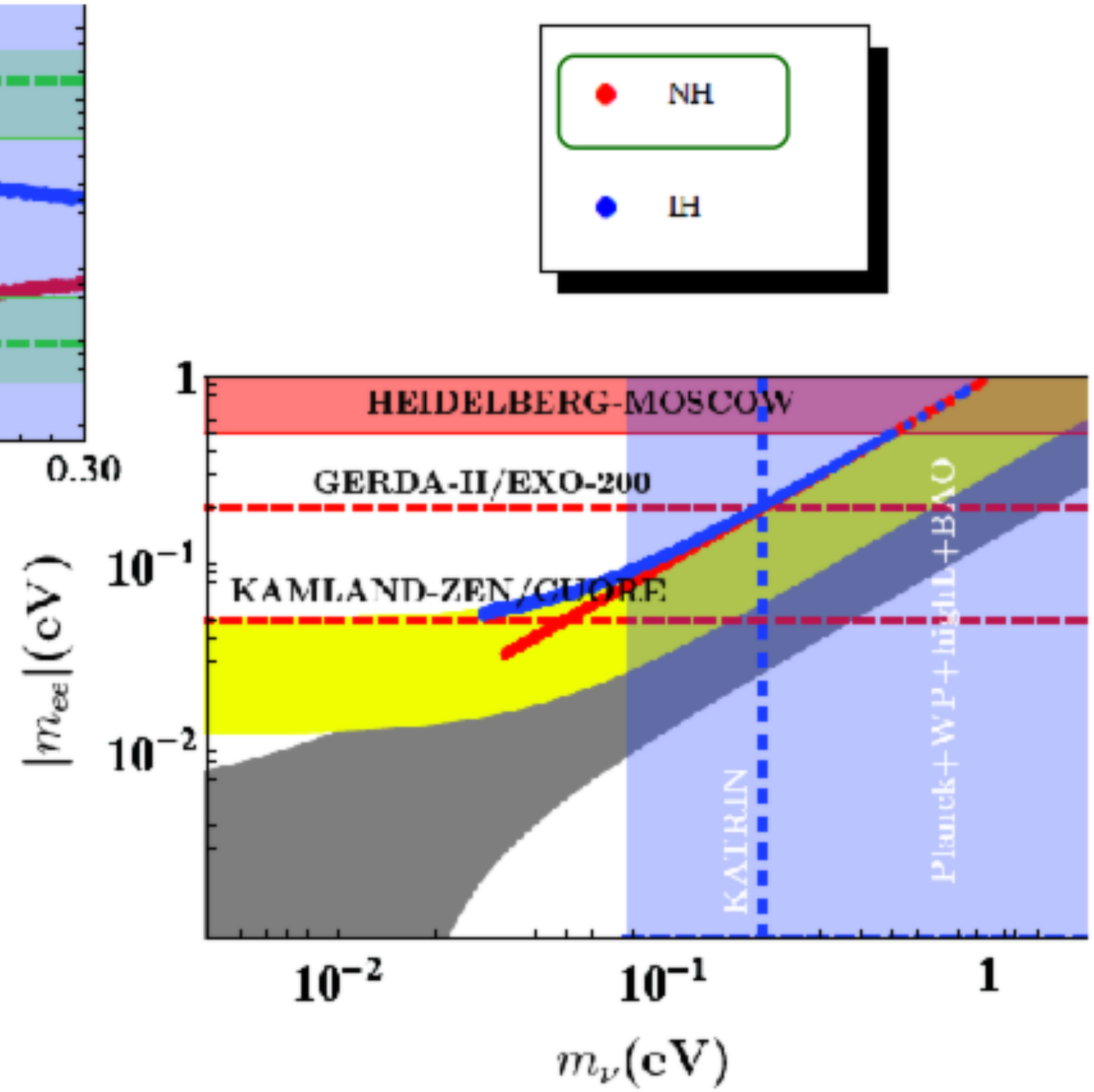
Meloni, Meroni, EP
Phys.Rev. D89 (2014) 5, 053009

Normal spectrum

Meloni, Meroni, Peinado

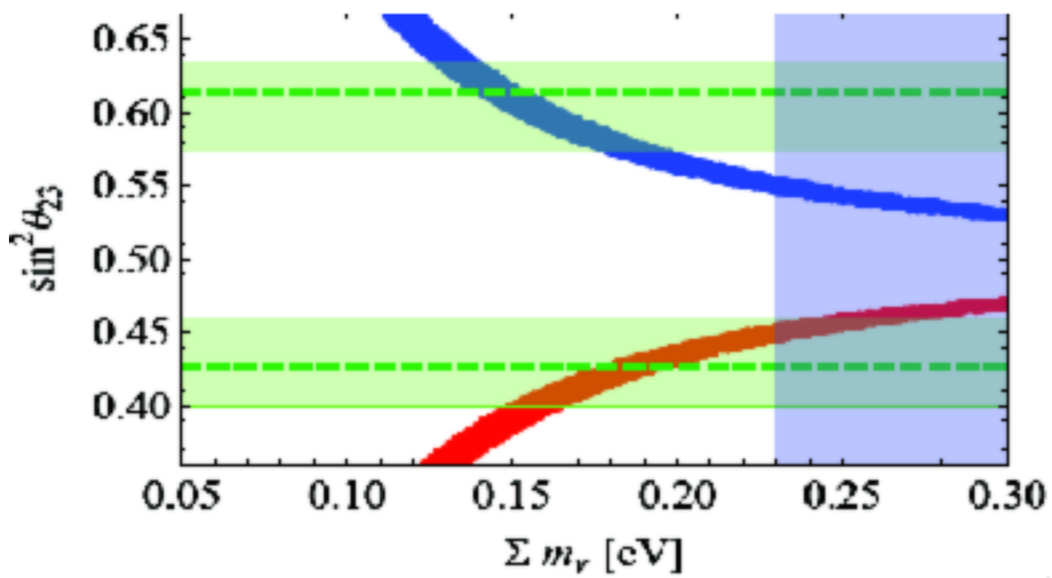
Normal Hierarchy





Normal spectrum

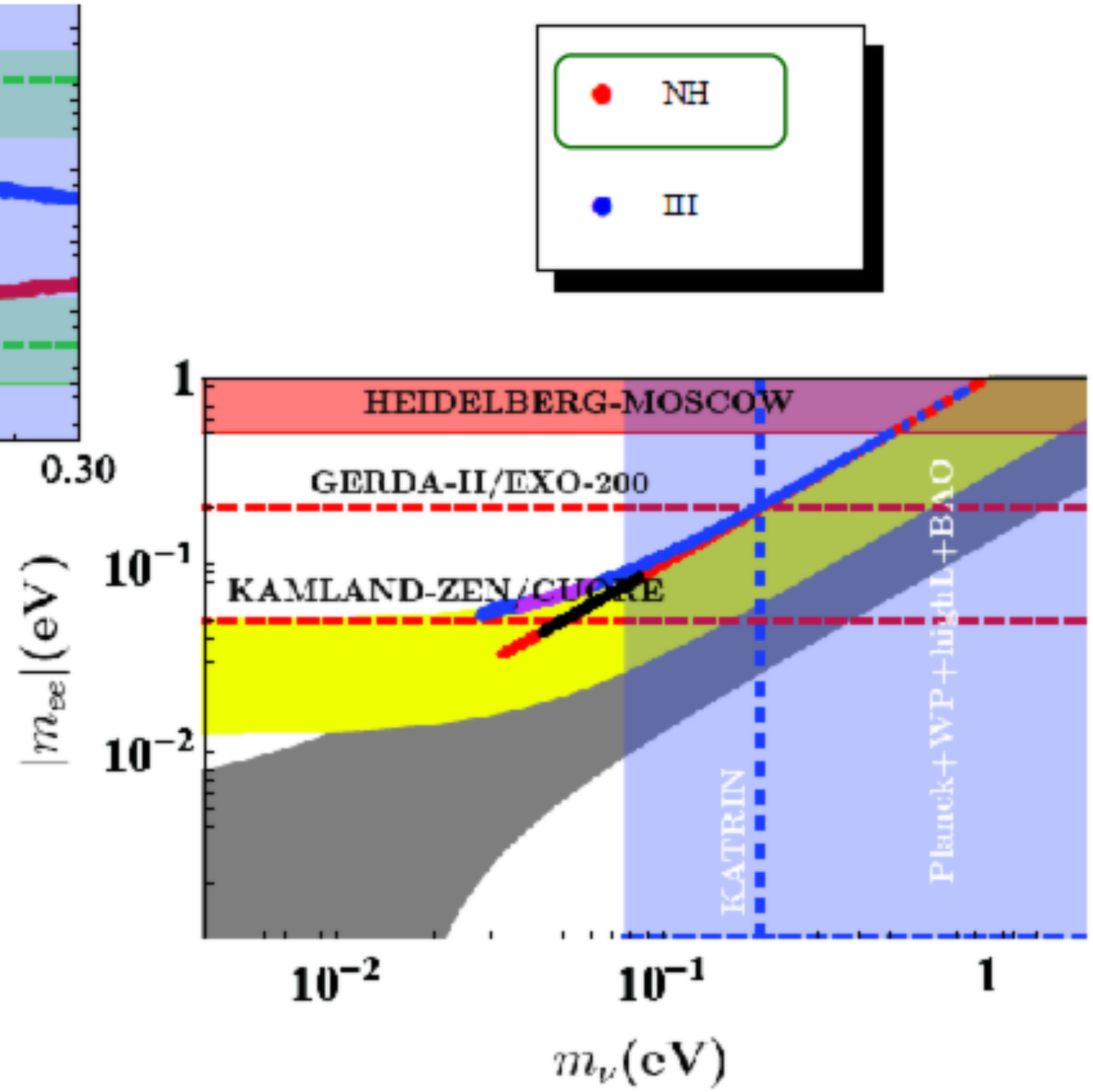
Normal Hierarchy



Could be excluded soon!!!

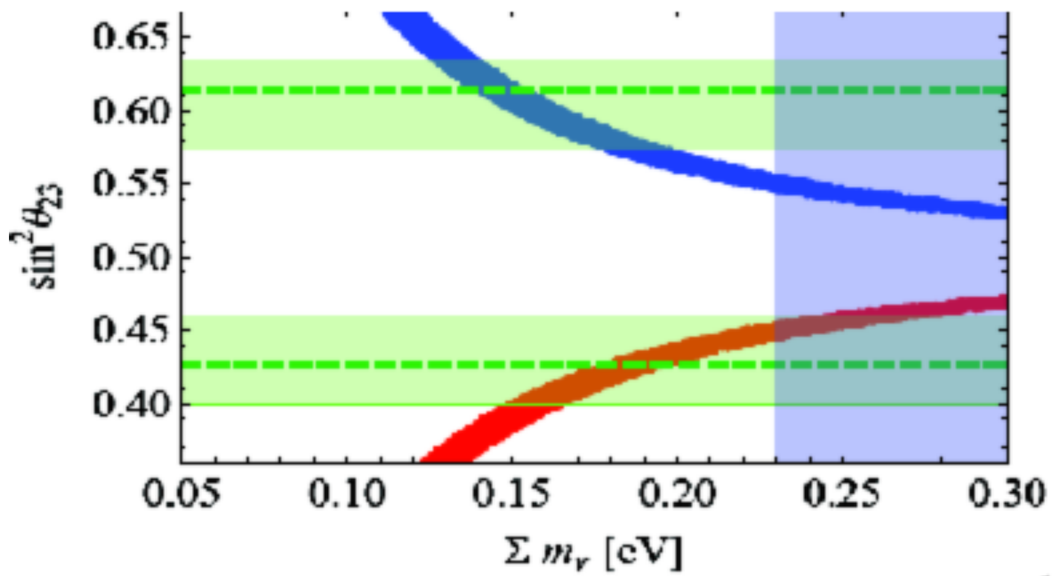
:)

Peinado, in progress...



Inverted spectrum

Inverted Hierarchy



Could be excluded soon!!!

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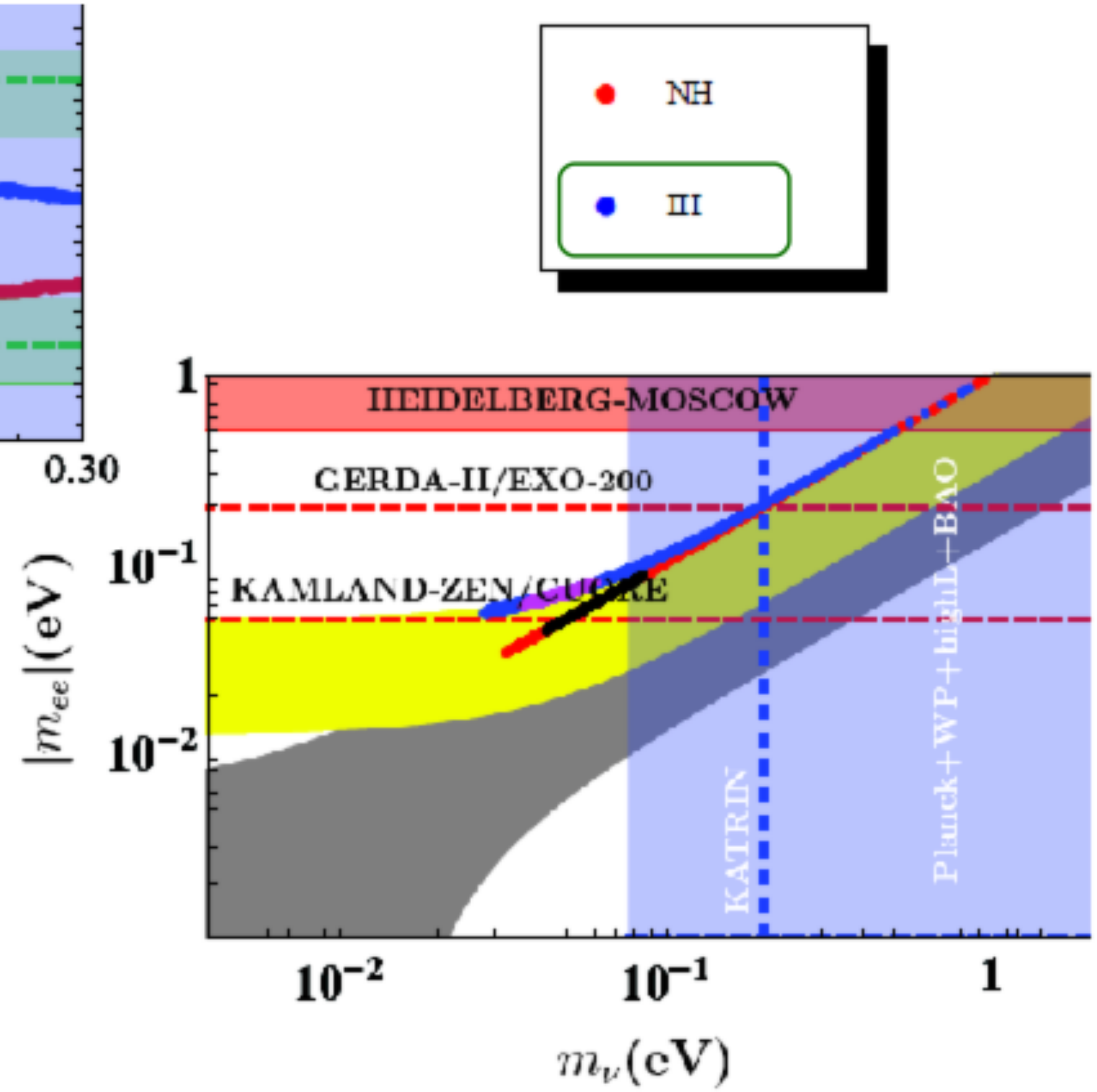
Peinado, in progress...



Conclusions

- We have evidence of “physics beyond the SM”
- It is interesting to find scenarios where some of them have a common explanation
- neutrino physics is a nice “portal to PBSM”
- DM stability and neutrino physics can be related
- Neutrino and BAU also related
- why not neutrinos - DM - BAU

Thank you very much for your attention