Beyond Standard Model and Neutrino Physics

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Reunion Anual de la División de Partículas y Campos

DPyC SMF

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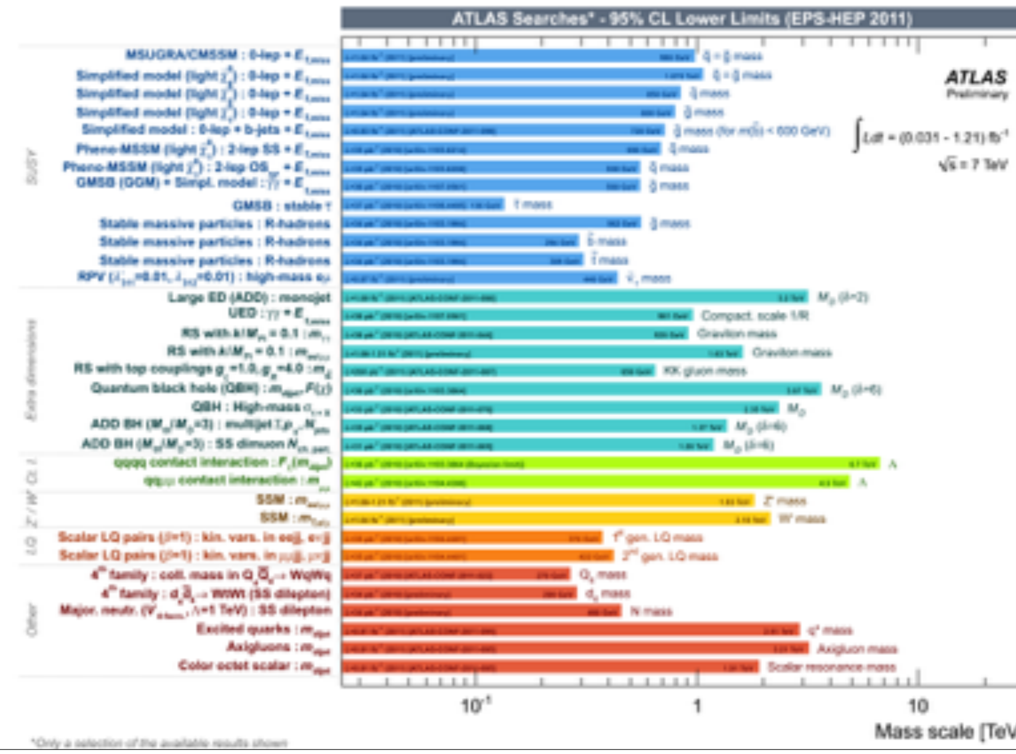
BSM

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

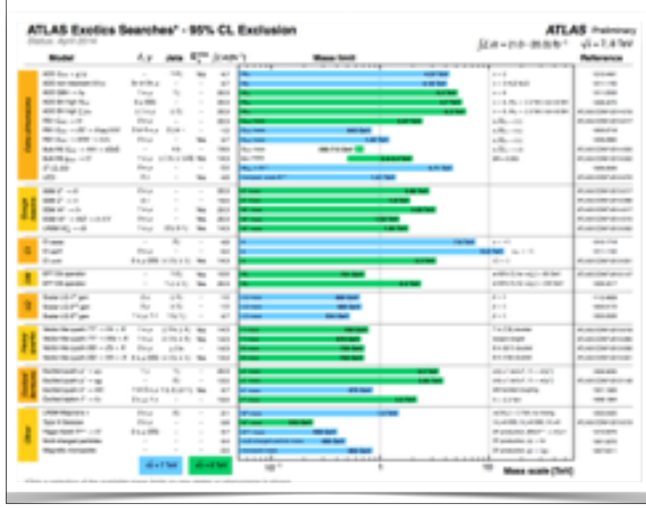
Infinite possibilities

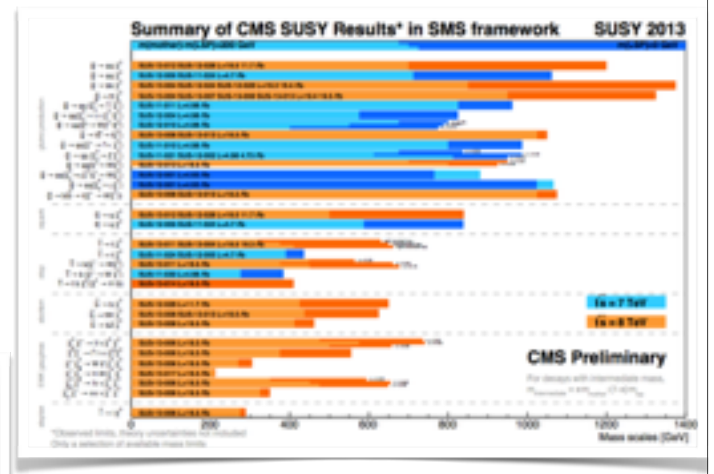
H. Murayama

- 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!!!

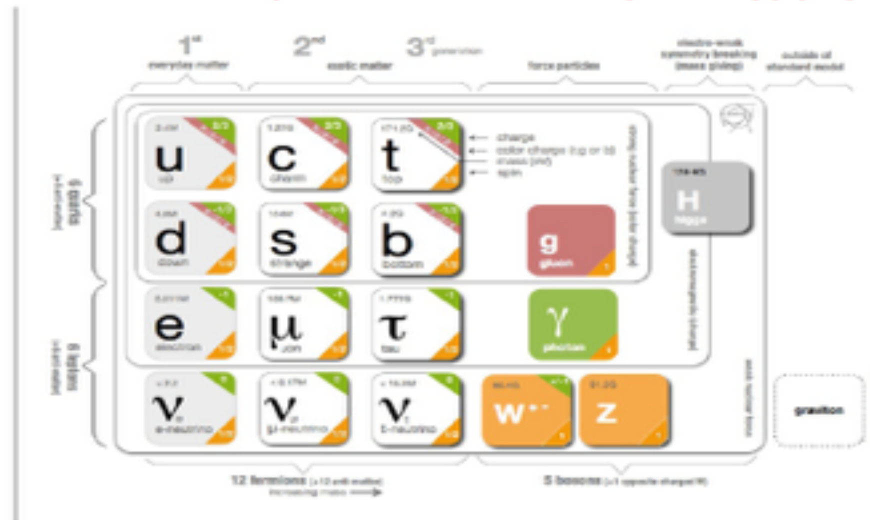
Outline

- **Introduction**
  - The SM
- **Neutrino physics**
  - SeeSaw Mechanism
- **Extensions of the SM**
- **Conclusions**

The SM

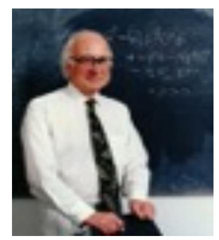
$$SU_c(3) \times SU_L(2) \times U_Y(1)$$

"Mendeleev periodic table" for high energy physics



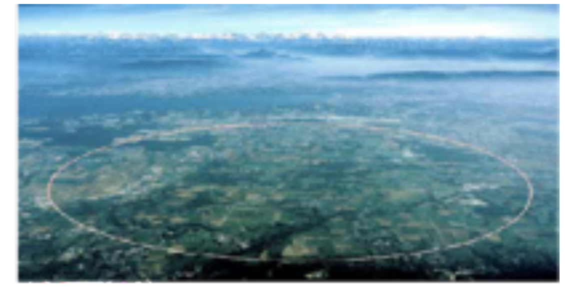
The SM

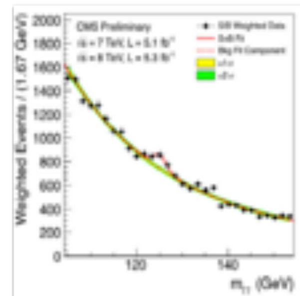
- The theory describes the fundamental interactions among particles
- Based on principle of gauge symmetry
- The Higgs Mechanism

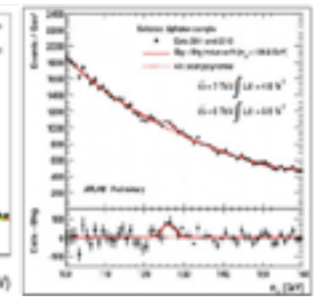


1968 u	1974 c	1995 t	1979 g
1968 d	1947 s	1977 b	1923 γ
1956 ν_e	1962 ν_μ	2000 ν_τ	1983 W
1897 e	1937 μ	1976 τ	1983 Z

The Higgs mechanism for particle masses



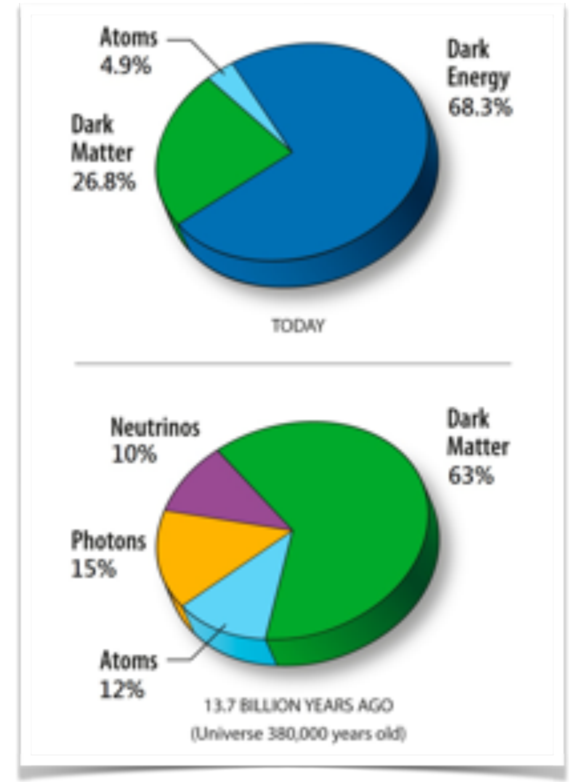




the theory is complete…
but
what about neutrino
physics?
cosmology?

Evidence of Physics BSM

- 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 …



Neutrinos


ELECTRON-NEUTRINO
ν_e
The ELECTRON-NEUTRINO wears a bandit's mask because he likes to steal away energy and is notoriously difficult to detect. Traveling close to the speed of light, he is the most pervasive form of matter in the universe Trillions of neutrinos are passing through everything around us, including us, at every moment. The result of radioactive neutron decay, most neutrinos originate from the sun. Their mass is next to nothing.
LIGHT
HEAVY
ELECTRON-NEUTRINO
The PARTICLE ZOO

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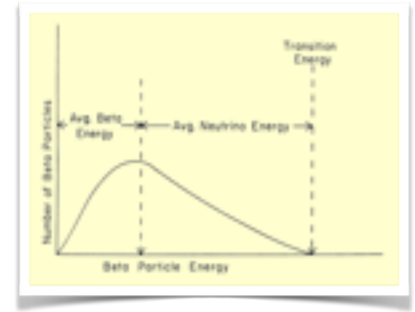
Neutrinos

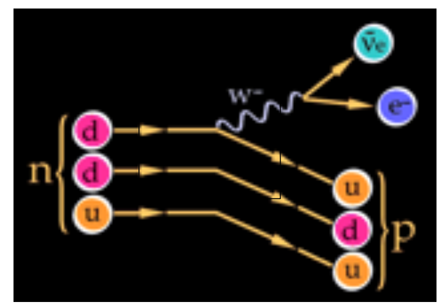
Neutrino short story

In 1930, Wolfgang Pauli postulated a new particle to explain the apparent non-conservation of energy in radioactive decays. But the theoretical particle he described had properties that made it so elusive that even Pauli wondered whether anyone would ever see it



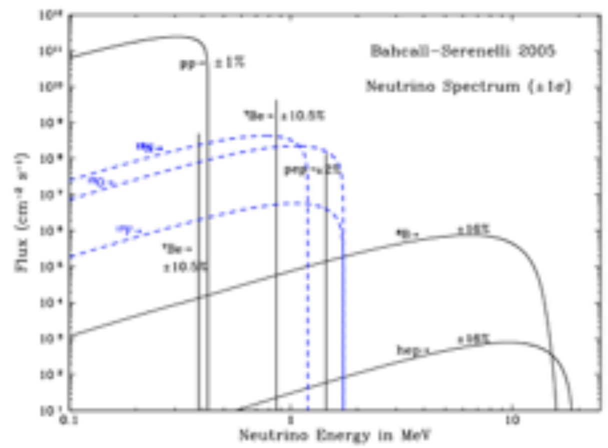
A revolutions starts that is not finished yet

By 1934, Enrico Fermi had developed a theory of beta decay to include the neutrino, presumed to be massless as well as chargeless.



Solar neutrino problem

Deficit of the solar neutrino flux



The pioneer experiment of Ray Davis were puzzled by the discrepancy between solar neutrino measurements and the expectations based upon the Standard Solar Model flux calculations

Eric's talk

Solar neutrino problem

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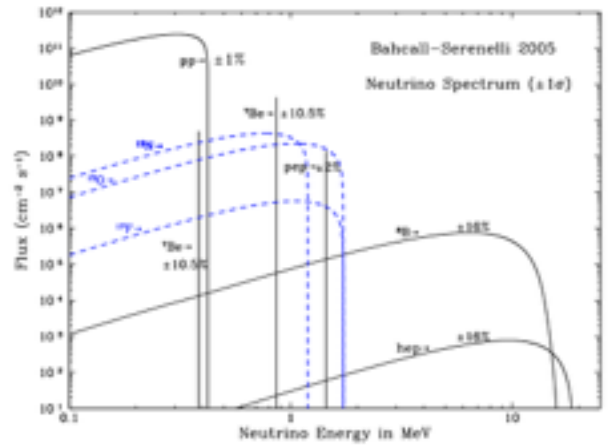

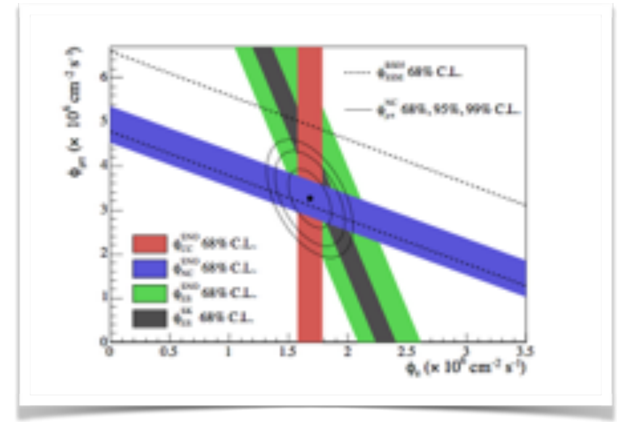

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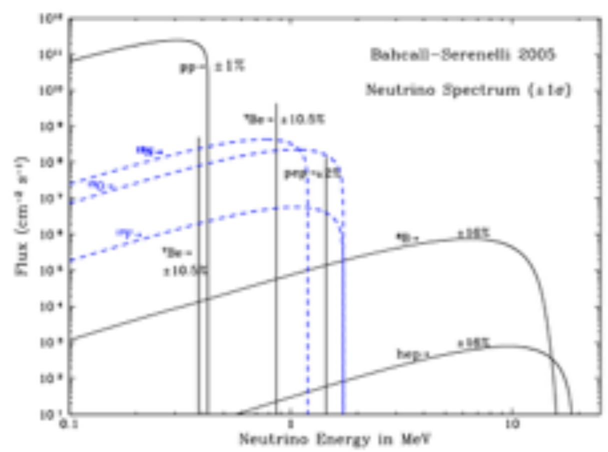

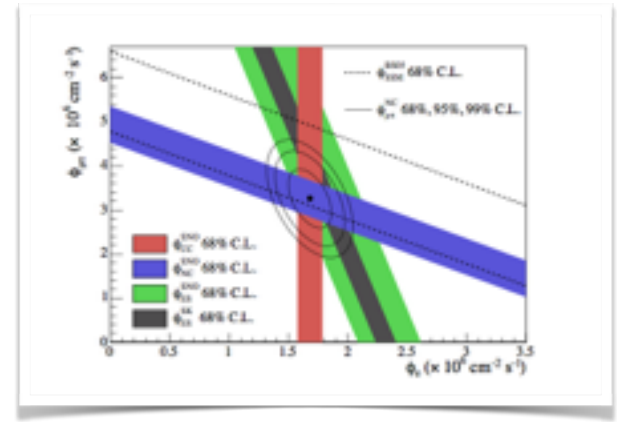

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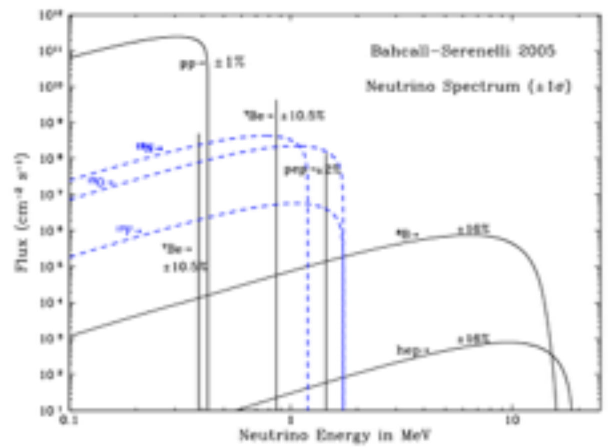

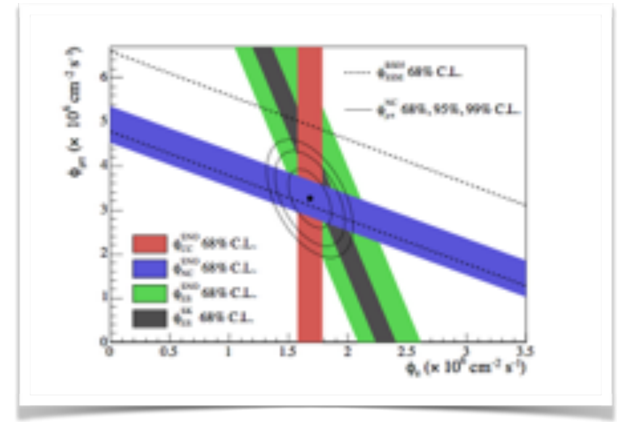

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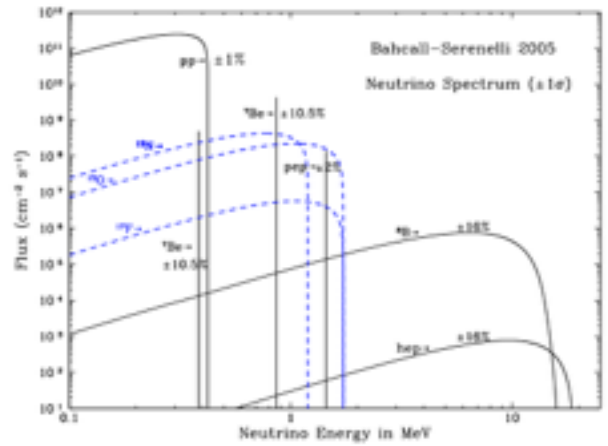

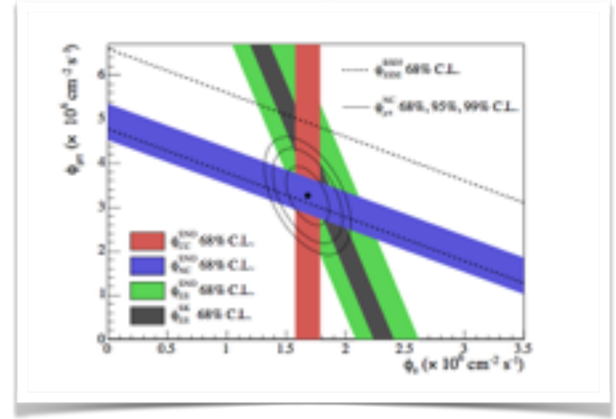

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neutrinos change flavour from the sun to the earth

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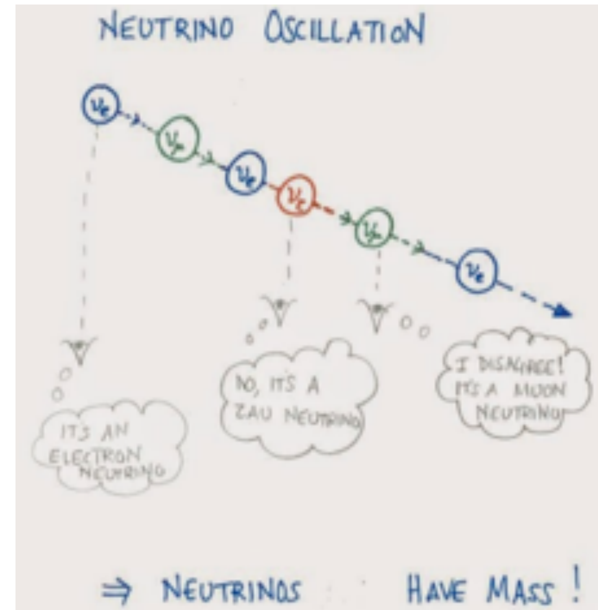
Eric’s talk

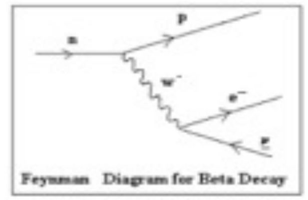
Neutrino physics

Neutrino Oscillation

Bruno Pontecorvo 1957

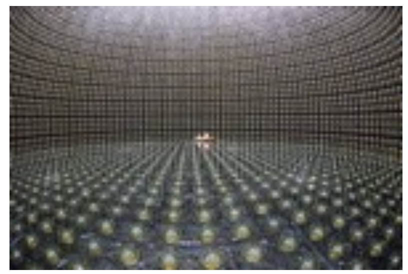


Neutrinos

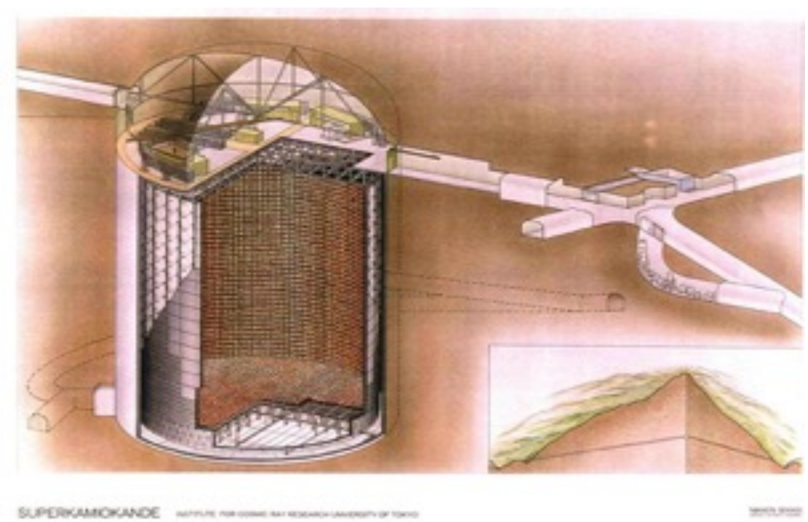


$$n \rightarrow p + e^- + \bar{\nu}_e$$

electron antineutrino



FACT: about 65 million neutrinos pass through your thumbnail every second.



50,000 tons of ultra-pure water.

Neutrino masses

how can we give mass to the neutrinos?

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$$\lambda_{\alpha i} \bar{L}_{\alpha} \epsilon H^{\star} N_i$$

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Violates lepton number

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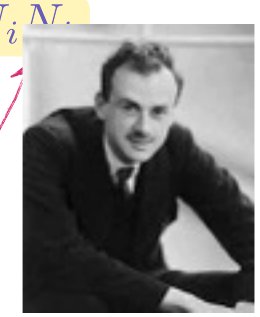
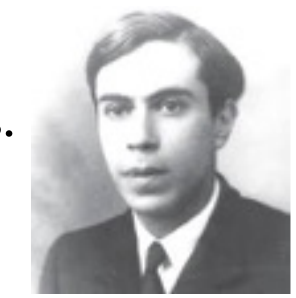


Vs.



If Dirac

Can be either

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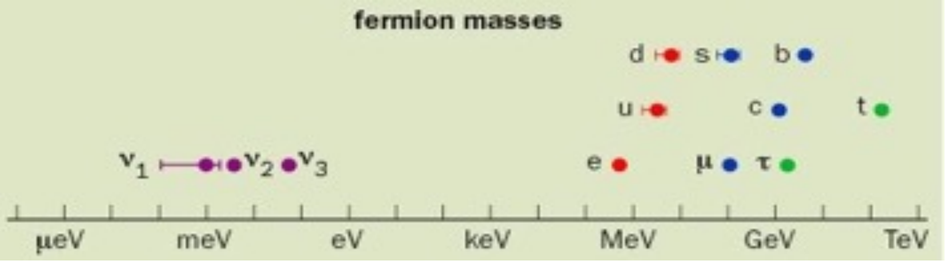
Can be either

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



- many orders of magnitude

$$m_\nu << m_e << m_t \qquad Y_{\nu_e} : Y_e : Y_t$$

The Yukawa couplings are very different

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

Majorana Neutrinos

If we allow L to be violated?

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

Majorana Neutrinos

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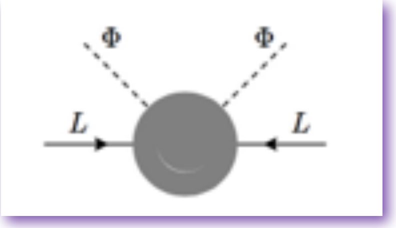
- **The simplest effective source of Majorana neutrino masses dim 5 Weinberg operator**



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?

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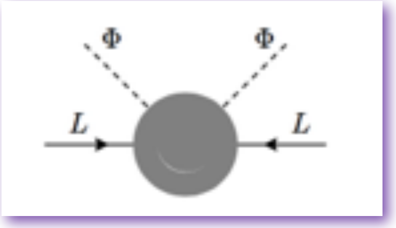

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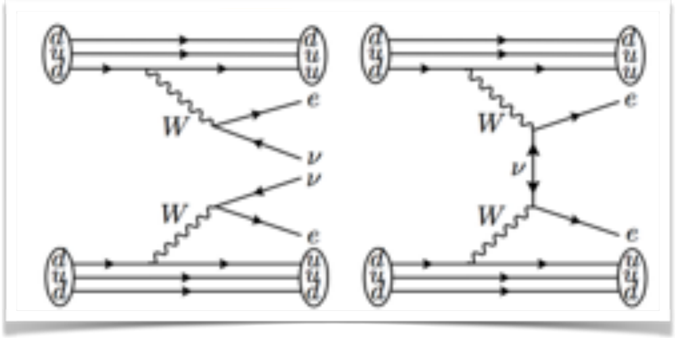
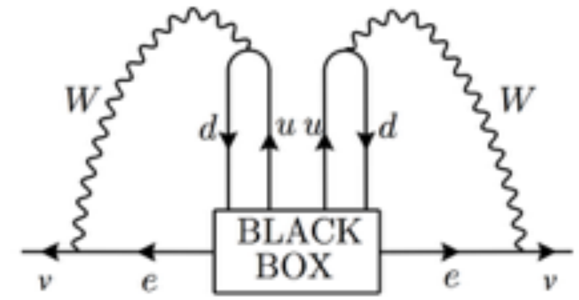
- Implications?

$$0\nu\beta\beta$$

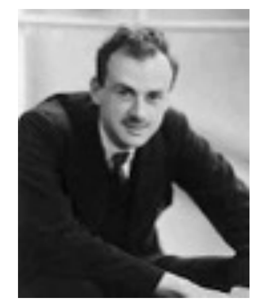


Black Box Theorem

If the neutrinoless double beta decay is observed that will imply a Majorana nature of the neutrinos



. Schechter, J. and Valle, J.W.F. (1982)



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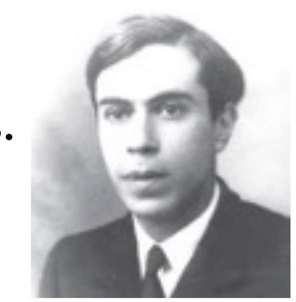

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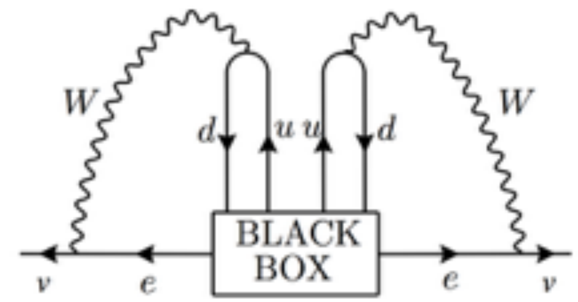

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Opening the box (UV completion)

seesaw

- We have several possibilities SU(2) doublets L

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

type I seesaw

LHN $\quad 2 \otimes 2 \otimes 1$

type II seesaw

$L\Delta L$ $\quad 2 \otimes 3 \otimes 2$

type III seesaw

$LH\Sigma$ $\quad 2 \otimes 3 \otimes 2$

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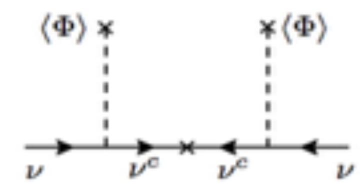
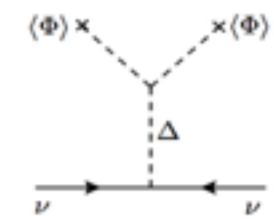


type I seesaw

LHN $\quad$ $2 \otimes 2 \otimes 1$



type II seesaw

$L\Delta L$ $\quad$ $2 \otimes 3 \otimes 2$

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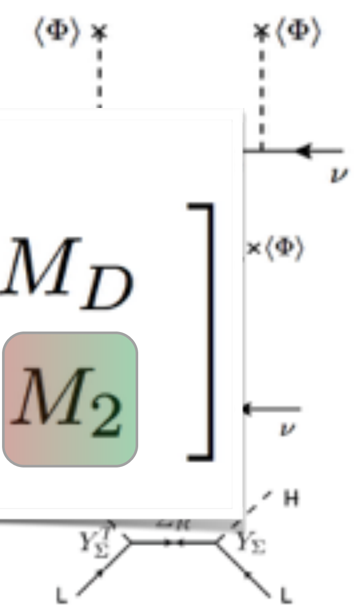

type I

type I

type II

$$\mathcal{M}_\nu = \begin{bmatrix} M_1 & M_D \\ M_D^T & M_2 \end{bmatrix}$$

$LH\Sigma$ $\quad 2 \otimes 3 \otimes 2$

Type III

More on see-saw

Linear see-saw

- New features emerge when the seesaw is realized with non-minimal lepton content (Isosinglets) SU(2) singlets: (ν_i^c,S_i) transforming as

$field$	L
ν_i	$+1$
N	-1
S_i	$+1$

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$$\mathcal{M}_\nu = \begin{bmatrix} 0 & Y_\nu^T \langle\Phi\rangle & 0 \\ Y_\nu \langle\Phi\rangle & 0 & M^T \\ 0 & M & \mu \end{bmatrix}$$

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violates L in 2 units

$\mu_{ij} S_i S_j$ mass terms

smallness of neutrino mass is related to the smallness of the parameter mu "natural" in the sense of 't Hooft

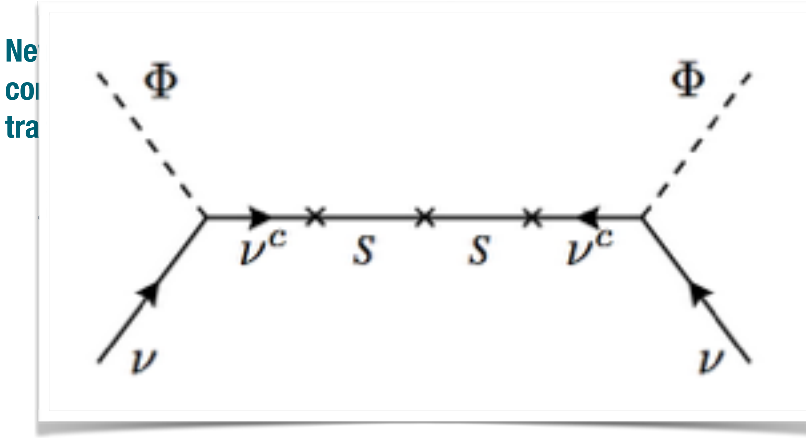
$$m_\nu \to 0 \quad \text{as} \quad \mu \to 0$$

t'Hooft, G. (1982)

More on see-saw

Linear see-saw

- Ne… mal lepton
  co…
  tra…



0

M^T

μ

violates L in 2 units

$$m_\nu{}^{\text{inverse}} = M_D M^{T^{-1}} \mu M^{-1} M_D^T.$$

m_ν

is related to the
… mu "natural" in
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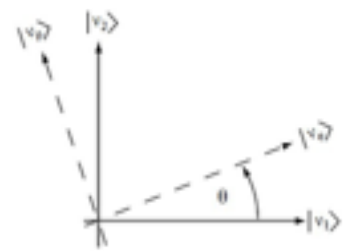
t'Hooft, G. (1982)

in the limit as $\mu \to 0$ the lepton number symmetry is restored,

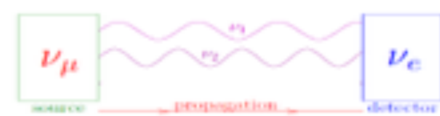
What do we know?

Neutrino oscillations 2 flavors



weak eigenstates mass eigenstates

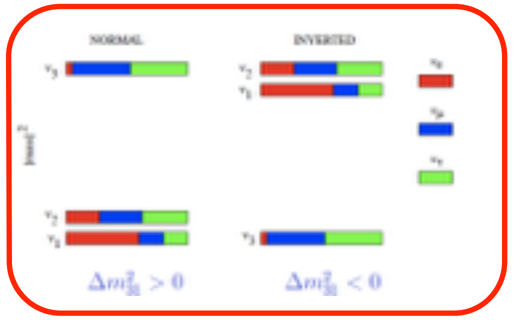
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$P(\nu_\mu \to \nu_e) = |\langle \nu_e | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E_\nu}\right)$$

3 mixing angles and 2 squared mass differences

What do we know?

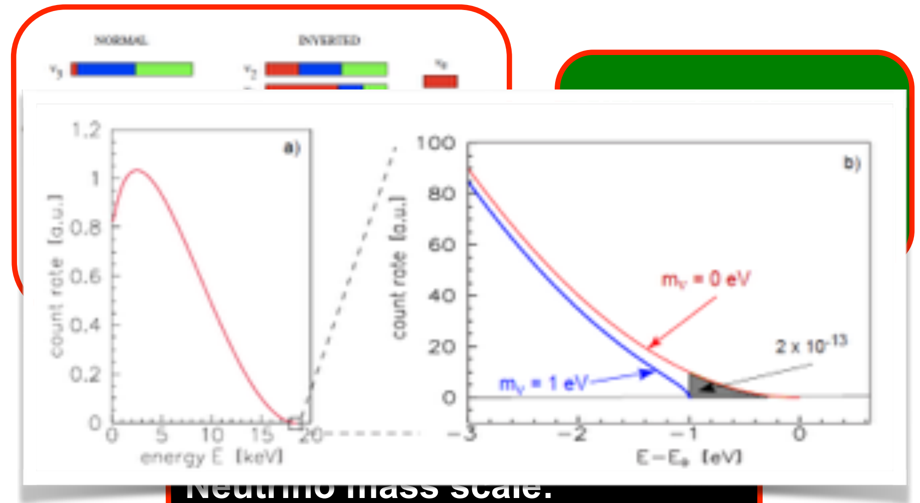


- Nature of neutrinos
- Absolute mass scale
- Mass ordering
- CP phases
- Precision in mixing angles

Neutrino mass scale:

Mainz current limit	Σ mν < 2 eV
Katrin future sensitivity	~ 0.2 eV
PLANK+BAO	Σ mν <0.23 eV

What do we know?



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Oscillation parameters

Tri-BiMaximal Mixing

Forero, Tortola and Valle, arXiv:1205.4018v2 [hep-ph]

parameter	best fit $\pm 1\sigma$
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.62 ± 0.19
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$
δ	$(0.83^{+0.54}_{-0.64})\,\pi$ 0.07π [a]

Daya Bay: $\sin^2\theta_{13}$ ~ 0.0235

CP mesurable??

tri-maximal

bi-maximal

Harriso, Perkin, Scott

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

Oscillation parameters

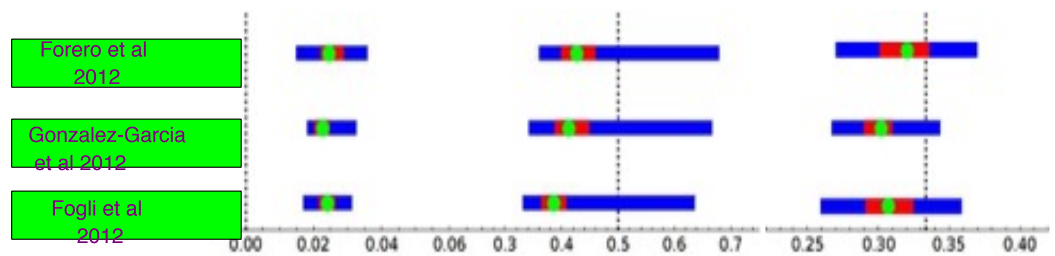
Tri-BiMaximal Mixing

Oscillation parameters

Tri-BiMaximal Mixing

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

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



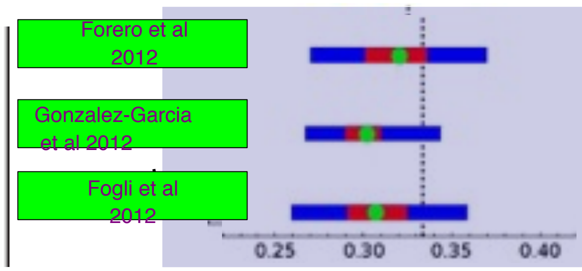
Oscillation parameters

Tri-BiMaximal Mixing

Oscillation parameters

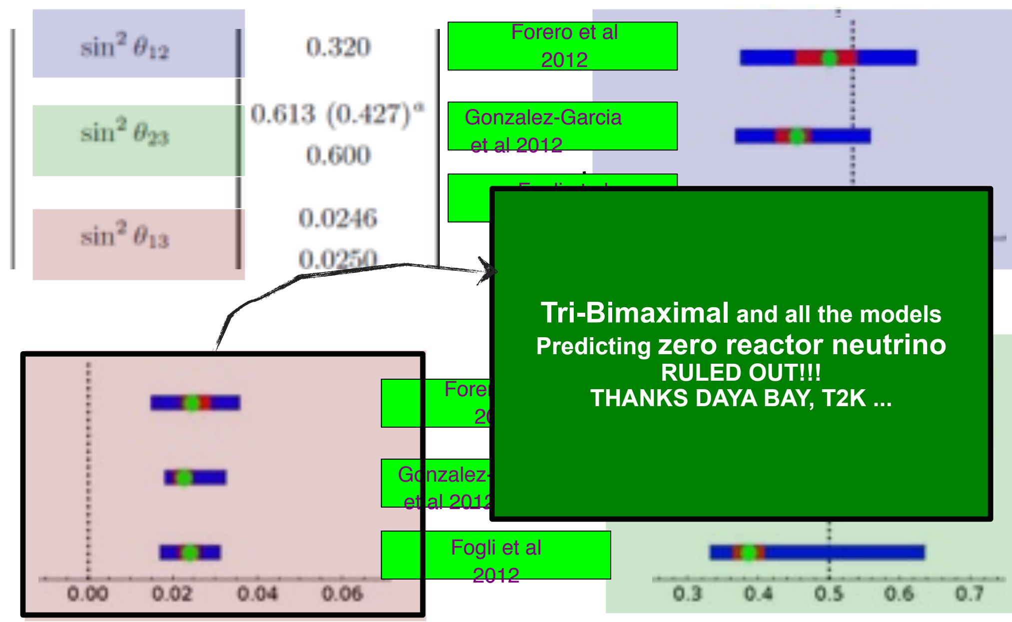
Tri-BiMaximal Mixing

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



Oscillation parameters

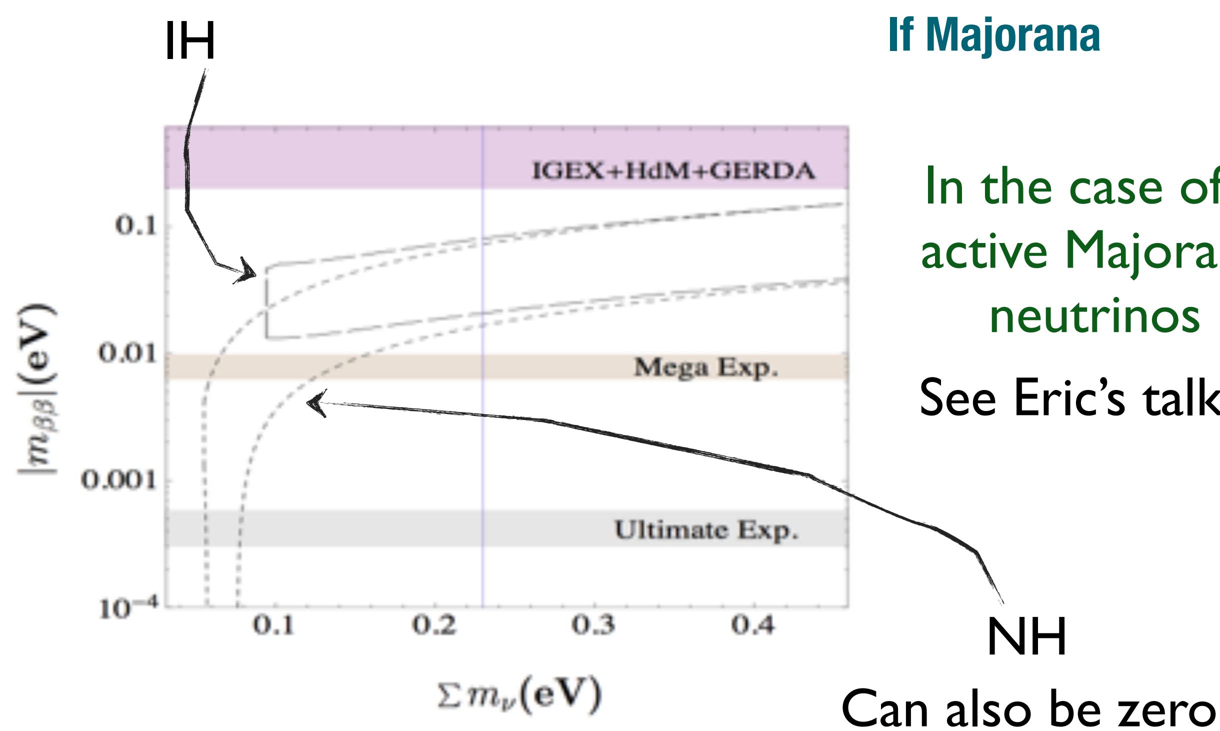
Tri-BiMaximal Mixing



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

Neutrinoless double beta decay

If Majorana



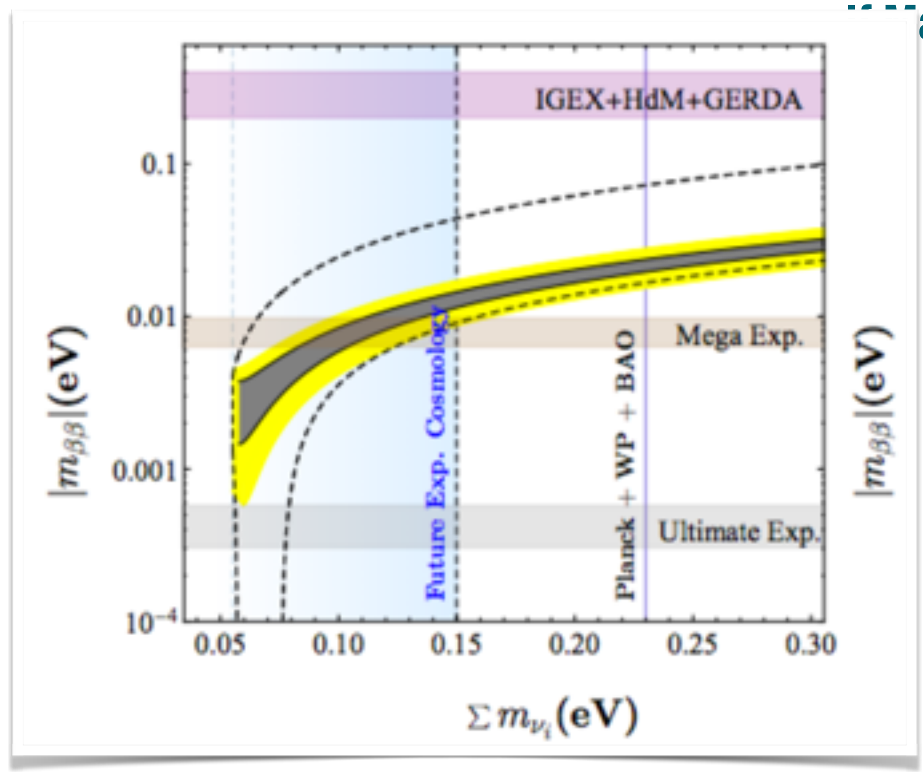
In the case of 3 active Majorana neutrinos

See Eric's talk

Neutrinoless double beta decay

If Majorana

Neutrinoless double beta decay

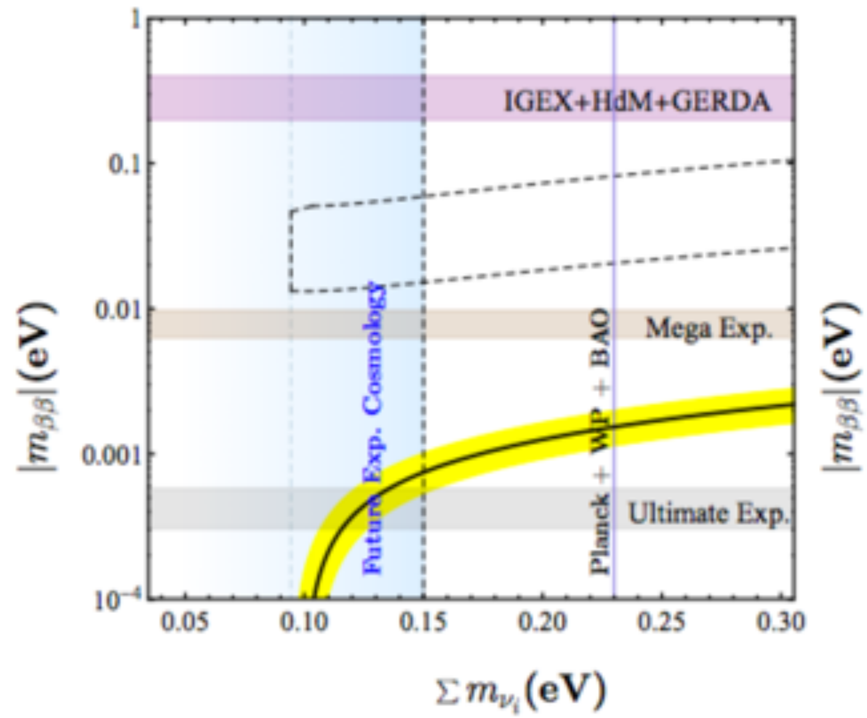


ajorana

1 Dirac + 2 Majorana

Meroni and Peinado (2015)

Neutrinoless double beta decay



2 Dirac + 1 Majorana

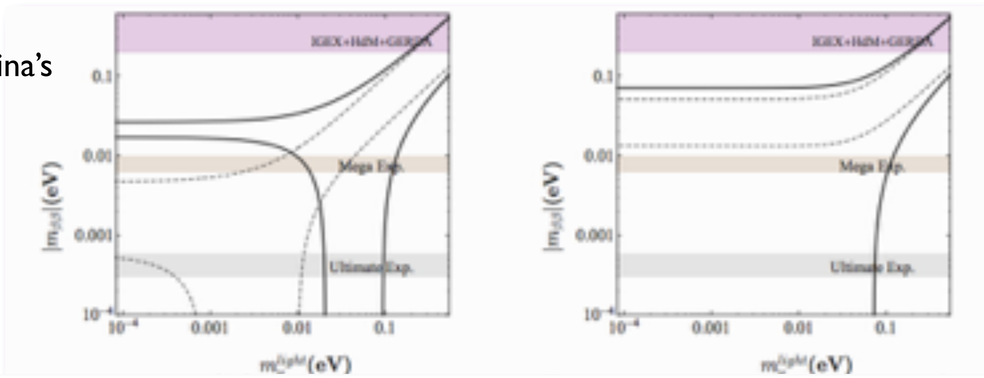
Meroni and Peinado (2015)

More exotic

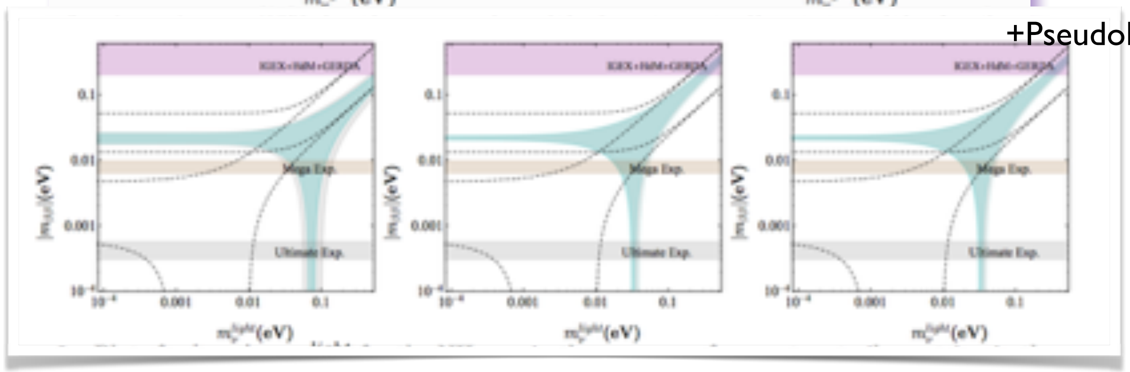
Meroni and Peinado (2015)

Messing with sterile

See Catalina's talk



+PseudoDirac



If type I see-saw

Light Neutrino Masses through see saw

Minkowski, Yanagida, Mohapatra, Senjanovic Sechter, Valle ...

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

⬇

$$m_\nu = -M^D \frac{1}{M_I} [M^D]^T$$

Baryon asymmetry and neutrino mass

The universe consists only on matter

Baryon asymmetry and neutrino mass

Sakharov's conditions for baryogenesis

- Baryon number violation

  If baryon asymmetry is conserved, no baryon number can be dynamically generated. There must exist $X^{B=0} \to Y^{B=0} + B^{B\neq0}$

- C and CP violation

  If C or CP are conserved, $\Gamma(X \to Y+B) = \Gamma(\bar{X} \to \bar{Y}+\bar{B}) \Rightarrow$ No net effect

- Departure from thermal equilibrium

  In thermal equilibrium, the production rate of baryons is equal to the destruction rate: $\Gamma(X \to Y+B) = \Gamma(Y+B \to X)$
  $\Rightarrow$ No net effect.

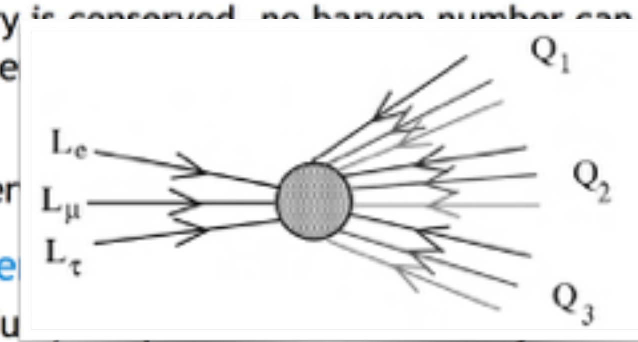
Baryon asymmetry and neutrino mass

Sakharov's conditions for baryogenesis

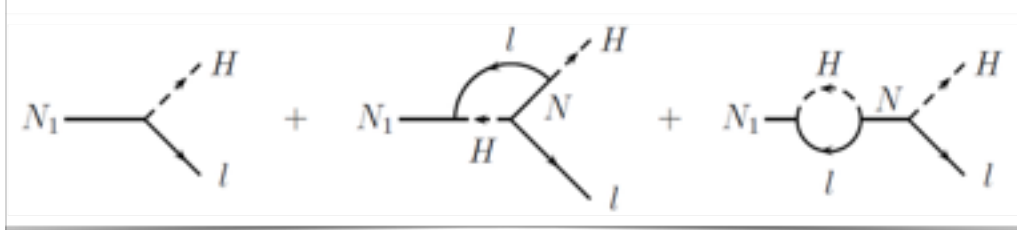
sphalerons violates B and L
preserves B-L
't Hooft

B-L

- Baryon number violation
  If baryon asymmetry is conserved, no baryon number can
  be dynamically gene ≠0
- C and CP violation
  If C or CP are conser ffect
- Departure from the
  In thermal equilibriu
  is equal to the destruction rate: $\Gamma(X \to Y+B) = \Gamma(Y+B \to X)$
  $\Rightarrow$ No net effect.



Leptogenesis



If complex Yukawa couplings
CP violation

Fong, Gonzalez-Garcia, Nardi, Peinado (2013)
Aristizabal-Sierra, Fong, Nardi, Peinado (2014)

The simplest way to neutrino masses: Type I see-saw

Minkowski(1977), Yanagida(1979), Gell-Mann et al. (1979), Glashow (1980), Mohapatra and Senjanovic (1981, Schechter and Valle (1980)

$$-\mathcal{L}_{\text{seesaw}} = \frac{1}{2} M_i \overline{N}_i N_i^c + \lambda_{\alpha i} \overline{\ell}_\alpha N_i \, \epsilon H^*$$

$$m_\nu \simeq -\lambda M^{-1} \lambda^T \langle H \rangle^2$$

We get for **free**: baryogenesis through leptogenesis [Fukugita and Yanagida (1986)]

Conventional Type-I leptogenesis requires

$$M \gtrsim 10^9 \text{ GeV} \implies \lambda \sim 10^{-3}$$

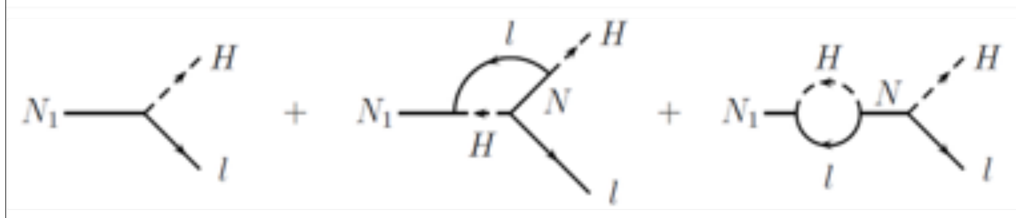
[Davidson and Ibarra (2002)]

Resonant leptogenesis

$$M \sim 10^3 \text{ GeV} \implies \lambda \sim 10^{-6}$$

[Pilaftsis (1997)]

Leptogenesis



If complex Yukawa couplings
CP violation

The simplest way to neutrino masses: Type I see-saw

Fong, Gonzalez-Garcia, Nardi, Peinado (2013)
Aristizabal-Sierra, Fong, Nardi, Peinado (2014)

Consider a scenario which fulfills:

(i) type-I seesaw at the TeV scale

(ii) leptogenesis at $T \sim O(\text{TeV})$

(iii) testable at the LHC via direct production of N and of *the new scalars*

We ge...

Conventional Type-I leptogenesis requires

$$M \gtrsim 10^9 \text{ GeV} \implies \lambda \sim 10^{-3}$$

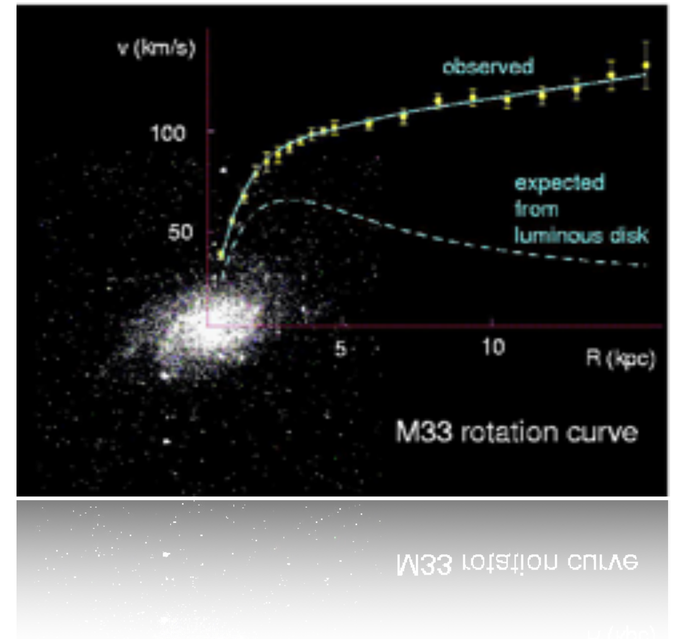
[Davidson and Ibarra (2002)]

Resonant leptogenesis

$$M \sim 10^3 \text{ GeV} \implies \lambda \sim 10^{-6}$$

[Pilaftsis (1997)]

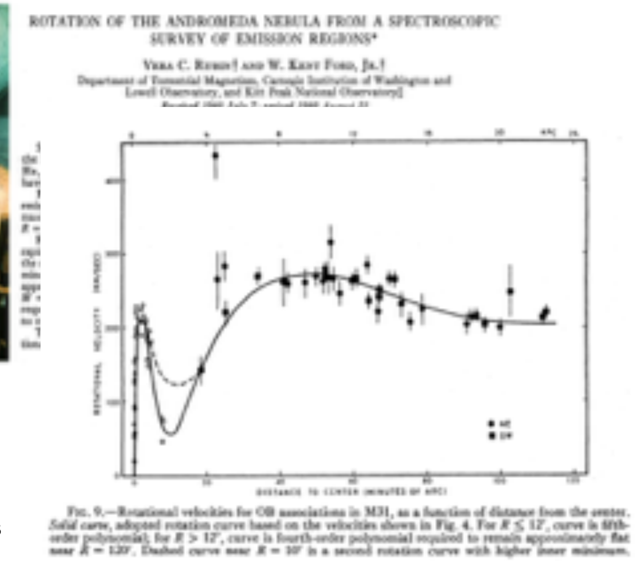
Zwicky 1933



See one of Eric's Talks

Dark Matter

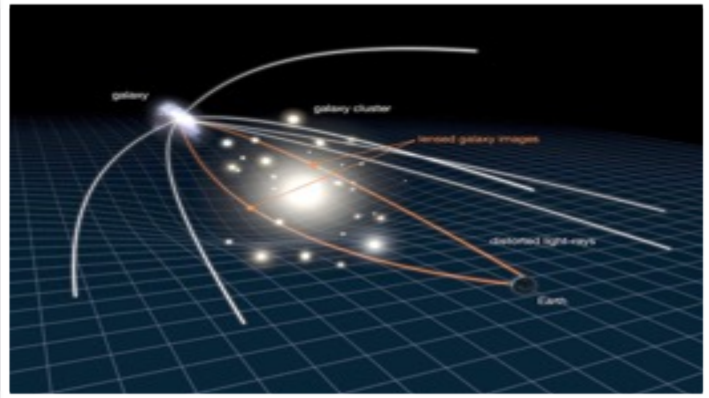
Not only in the clusters of galaxies



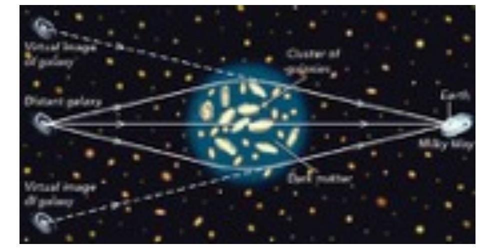
Vera Rubin
70's

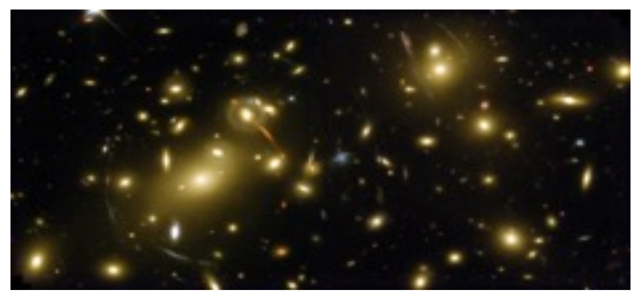
Velocidad de las estrellas
en la galaxia andromeda

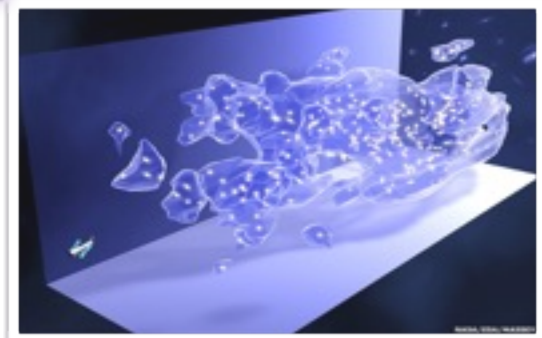
DM evidence



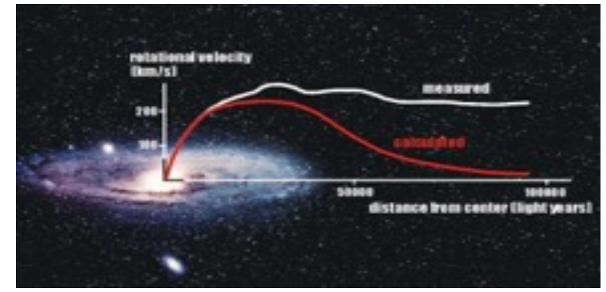
Gravitational lensing

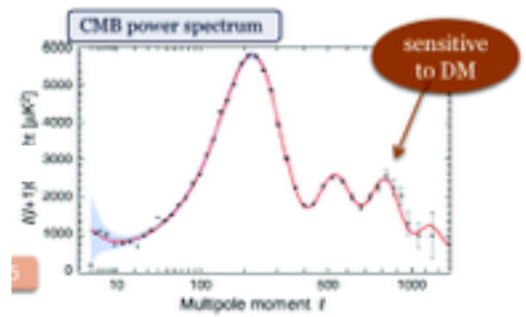


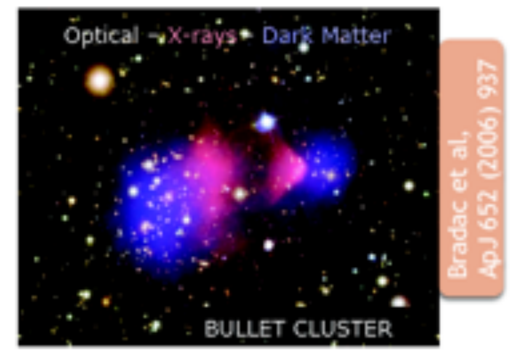




- Rotational curves
- Clusters of galaxies
- CMB anisotropies
- BBN
- ...

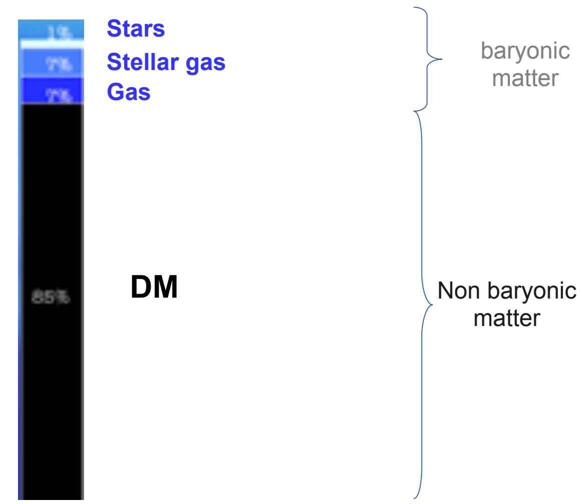






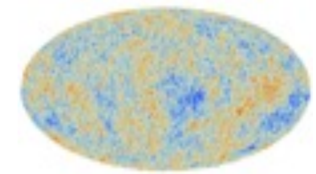
See one of Eric’s Talks

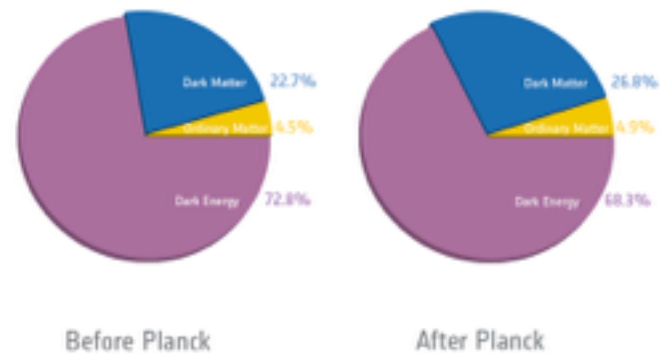
Inventary of matter in the universe



What do we “know” about DM?

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



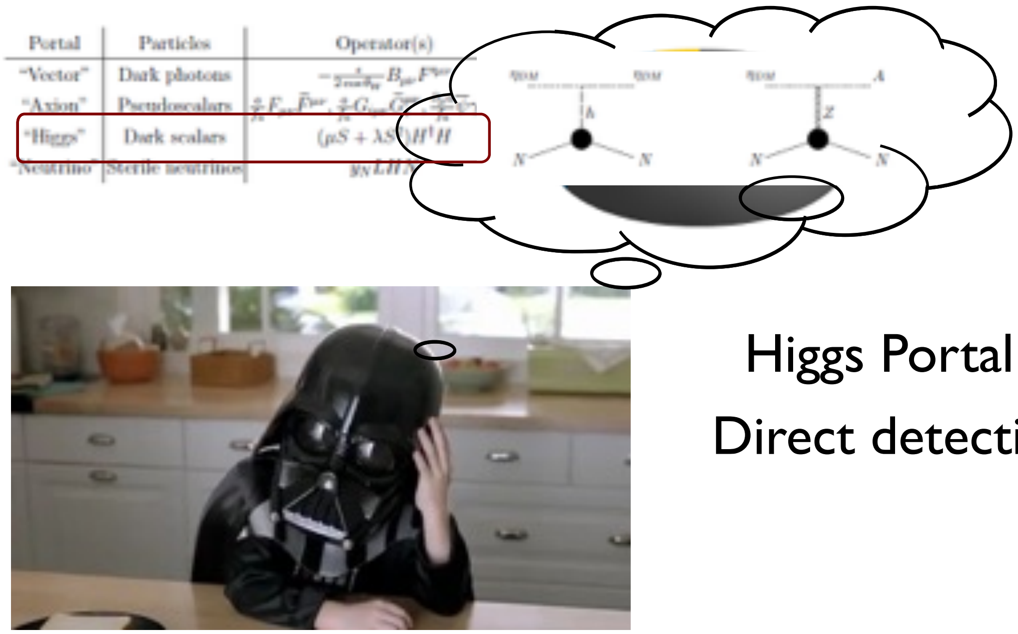


What do we “know” about DM?

- 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



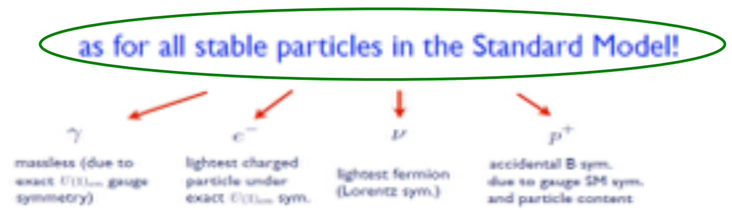
Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i\mu\nu}\tilde{G}^{\mu\nu}_i$ [illegible]
"Higgs"	Dark scalars	$(\mu S + \lambda S^2)H^\dagger H$
"Neutrino"	Sterile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

Higgs Portal

Direct detection

One simple Idea for DM

Inert scalar DM



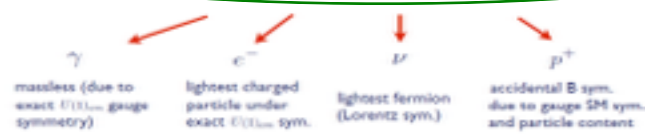
One simple Idea for DM

Inert scalar DM

Deshpande and Ma (1978)

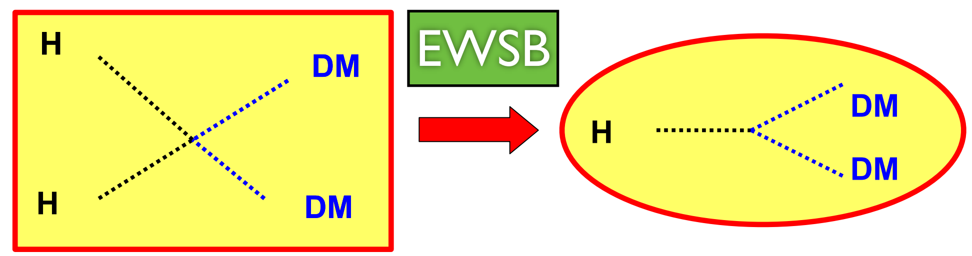
SM + scalar

as for all stable particles in the Standard Model!



Z_2 **+**   **-**

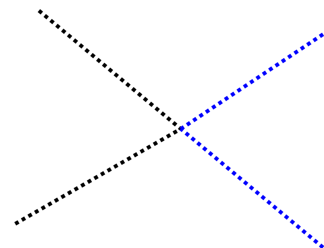
$$\lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$



Higgs portal

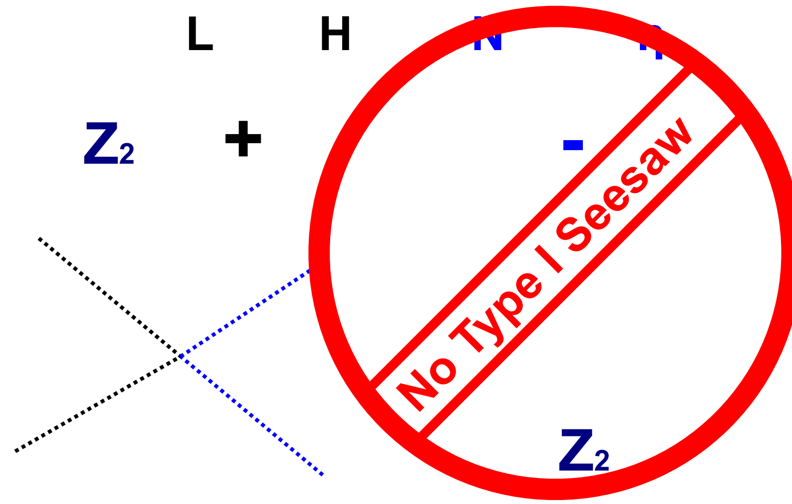
Neutrino masses in the Inert DM?

	L	H	N	η
Z_2	+		-	



$$\langle\eta\rangle = 0 \xrightarrow{Z_2} m_D = 0$$

Neutrino masses in the Inert DM?



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

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

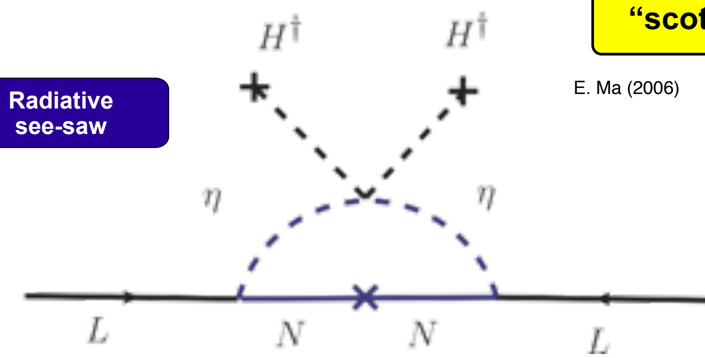
Neutrino masses in the inert DM

A. Zee (1980)

“scotogenic”

E. Ma (2006)

Radiative see-saw

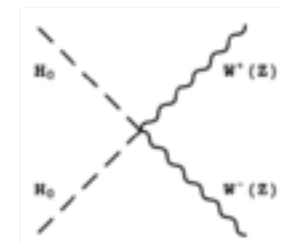


If $M_k^2 >> m_0^2$, then

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

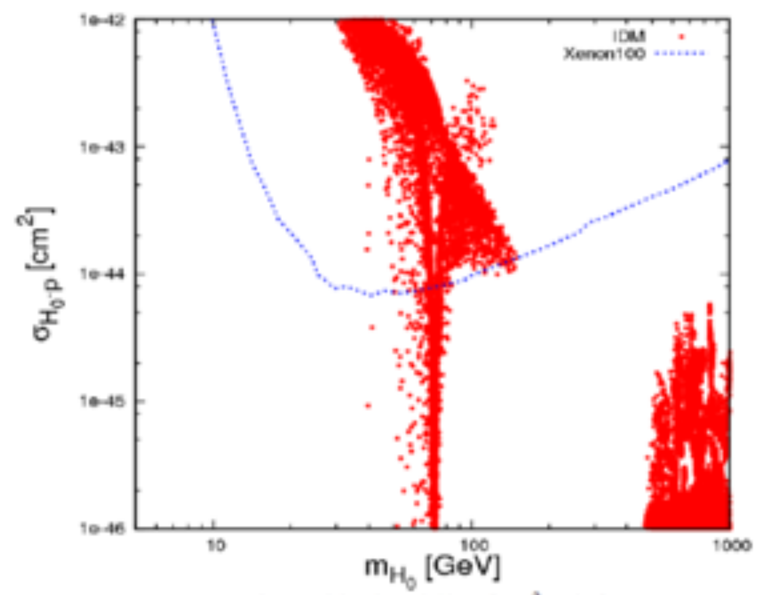
Minimal spirit: SM + one SU(2) doublet
or another multiplet (fermionic or scalar)
The stability -------> Z2 symmetry

Extra quartic couplings with the Higgs
but also with the gauge bosons

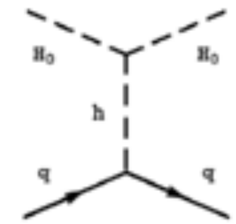


Ωh^2

Direct Detection



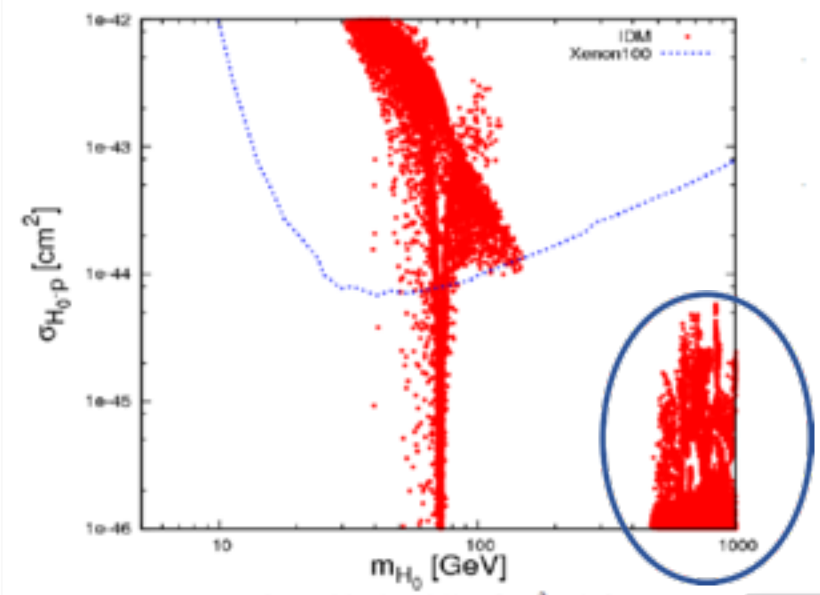
result of a scan giving rise to $0.09 < \Omega_{H_0} h^2 < 0.13$



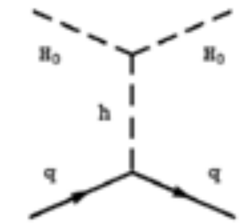
$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2} \right)^2$$

Laura Lopez-Honorez

Direct Detection



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



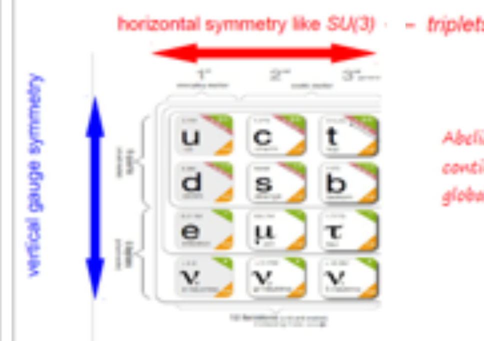
$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2}\right)^2$$

High mass regime

Laura Lopez-Honorez

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



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

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

A4 and TBM

$\langle \phi \rangle = (1,1,1)$ $\rightarrow$ Z_3 $\rightarrow$ M_l

$\langle \phi' \rangle = (1,0,0)$ $\rightarrow$ Z_2 $\rightarrow$ M_ν

Altarelli Feruglio (2005)

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

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)

We have symmetries (stability)?

Z3 in the charged sector X

Z2 in the neutrino sector

stabilize the DM

TBM X

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

We have symmetries (stability)?

Z2 in the charged sector Z2 in the neutrino sector

stabilize the DM

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

1, 1', 1'' 3

The simplest 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 simplest 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

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

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

$\langle \eta_1^0 \rangle = v_\eta$

$\langle H^0 \rangle = v_h$

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

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

Neutrino masses in the model

Scaling matrix,
Rodejohan and Mohapatra

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

Inverse mass Hierarchy

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

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

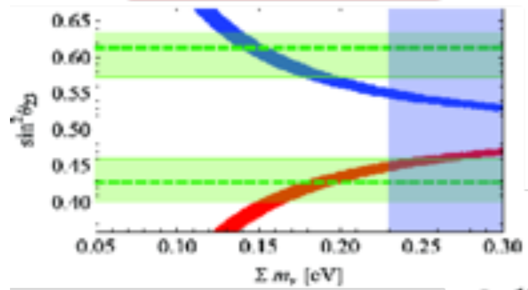
Now the FS will be broken
At the see-saw scale

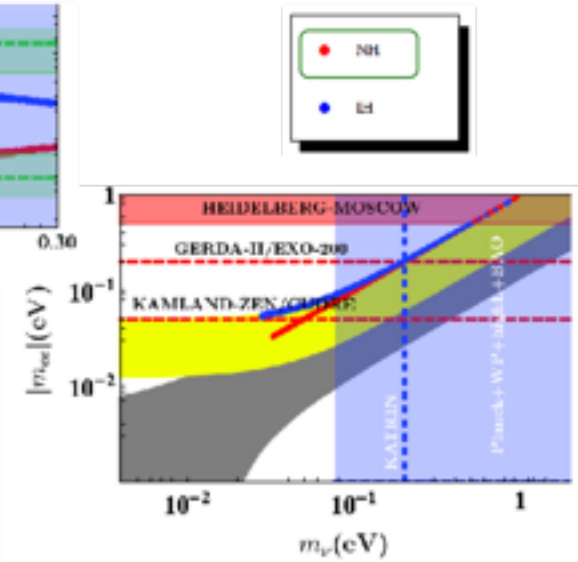
$$V_{lep} = U_l^{+} U_\nu$$

Normal spectrum

Normal Hierarchy

Meloni, Meroni, Peinado

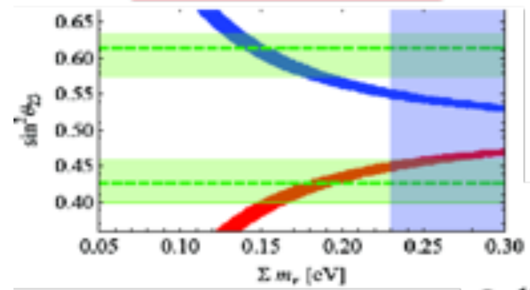




Normal spectrum

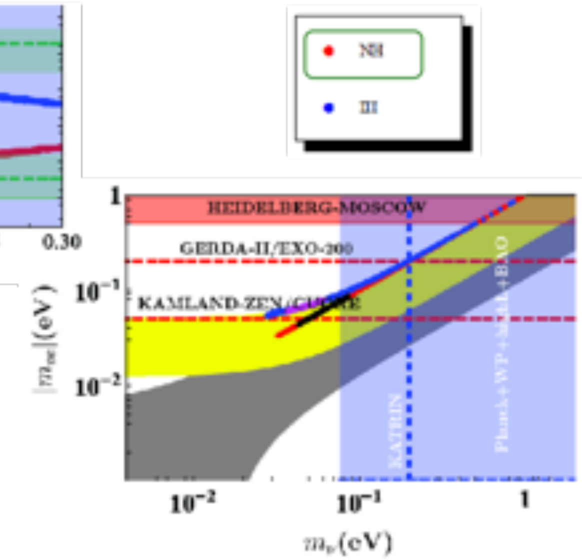
Normal Hierarchy

Peinado, in progress...



Could be excluded soon!!!

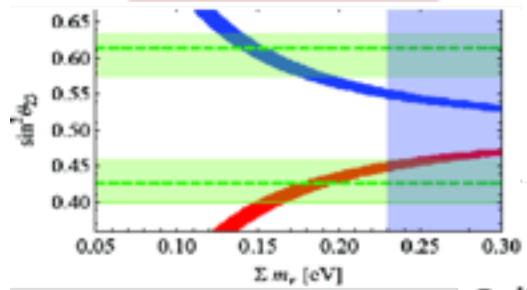
:)



Inverted spectrum

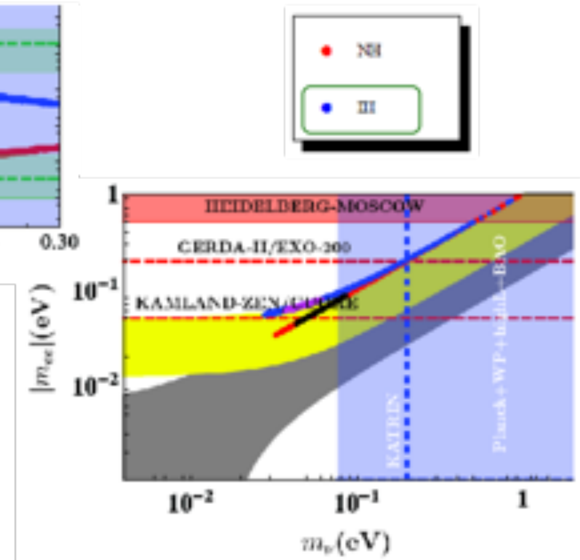
Peinado, in progress...

Inverted Hierarchy



Could be excluded soon!!!

:)



Susy and Proton decay

The superpotential

$$W = W^{MSSM} + W^{\not{R}_p}$$

Violates lepton number

$$W^{\not{R}_p} = \epsilon_{ab}\left[\frac{1}{2}\lambda_{ijk}\widehat{L}_i^a\widehat{L}_j^b\widehat{e}_k^c + \lambda'_{ijk}\widehat{L}_i^a\widehat{Q}_j^b\widehat{d}_k^c + \epsilon_i\widehat{L}_i^a\widehat{H}_u^b\right]$$

$$+\frac{1}{2}\lambda''_{ijk}\widehat{u}_i^c\widehat{d}_j^c\widehat{d}_k^c$$

Violates baryon number

Susy and proton decay

The superpotential

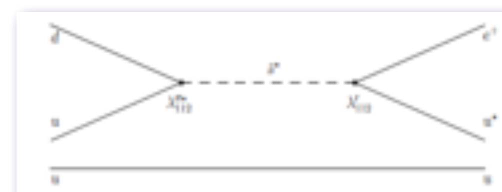
$$W = W^{MSSM} + W^{\not{R}_p}$$

$$W^{\not{R}_p} = \epsilon_{ab}\left[\frac{1}{2}\lambda_{ijk}\widehat{L}_i^a\widehat{L}_j^b\widehat{e}_k^c + \lambda'_{ijk}\widehat{L}_i^a\widehat{Q}_j^b\widehat{d}_k^c + \epsilon_i\widehat{L}_i^a\widehat{H}_u^b\right]$$

$$+ \frac{1}{2}\lambda''_{ijk}\widehat{u}_i^c\widehat{d}_j^c\widehat{d}_k^c$$

Hinchliffe, Kaeding (1993)
F. Vissani, (1995).
...

Proton decay



R-Parity

$$W^{\not R_p} = \epsilon_{ab}[\frac{1}{2}\lambda_{ijk}\widehat{L}_i^a\widehat{L}_j^b\widehat{e}_k^c + \lambda'_{ijk}\widehat{L}_i^a\widehat{Q}_j^b\widehat{d}_k^c + \epsilon_i\widehat{L}_i^a\widehat{H}_u^b]$$
$$+ \frac{1}{2}\lambda''_{ijk}\widehat{u}_i^c\widehat{d}_j^c\widehat{d}_k^c$$

Fayet, **Nucl. Phys. B90, 104 (1975).**
Farrar and Fayet, **Phys. Lett. B76**, 575 (1978).

$$R_p = (-1)^{3(B-L)+2s}$$

$R_p = +1$

$R_p = -1$

Breaking R-parity and neutrino masses

Hall and Suzuki (1984)
Mukhopadhyaya, Roy,Vissani (1998)

R-parity breaking gives a contribution to Majorana neutrino mass

Hirsch, Diaz, Porod, Romao, Valle (2000)

Bi-linear R-parity breaking can generate one neutrino mass, other two by radiative corrections

This case is similar to 1 RH neutrino, rank 1 matrix

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

Conclusions I

- It is interesting to find models where there is a connections among different 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

Just in case!!!

The alignment

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

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

$$Z_2$$

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

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

Z_2 residual symmetry

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

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

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

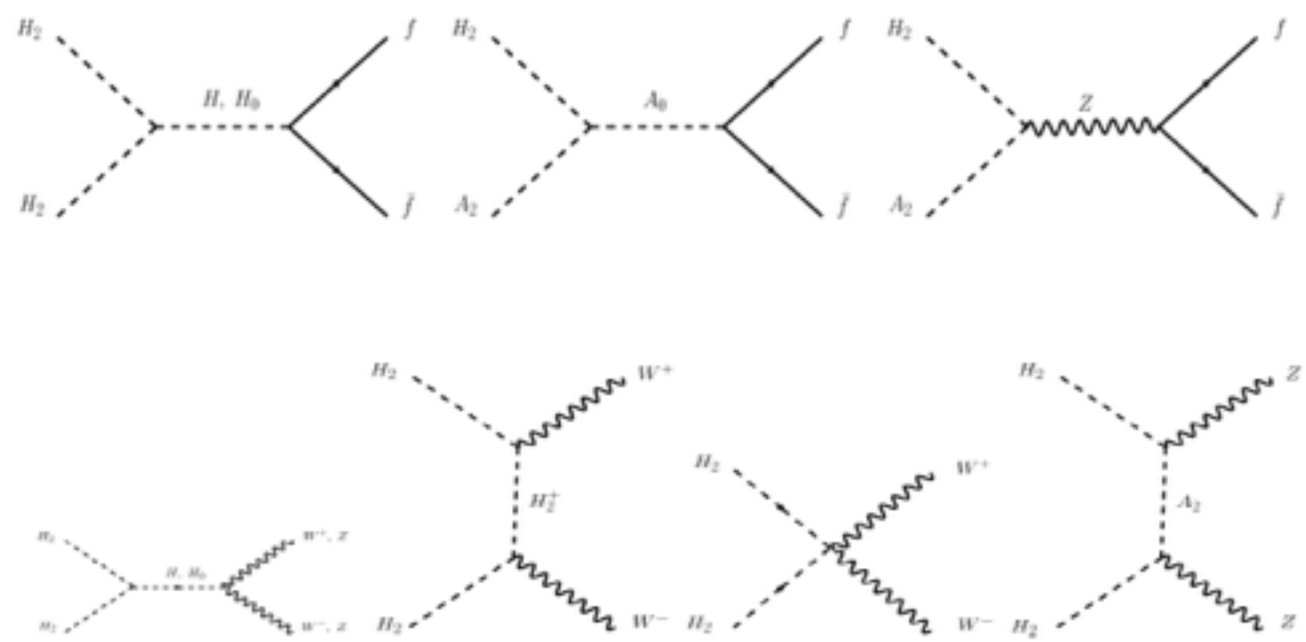
→ Z_2 even

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

→ Z_2 odd

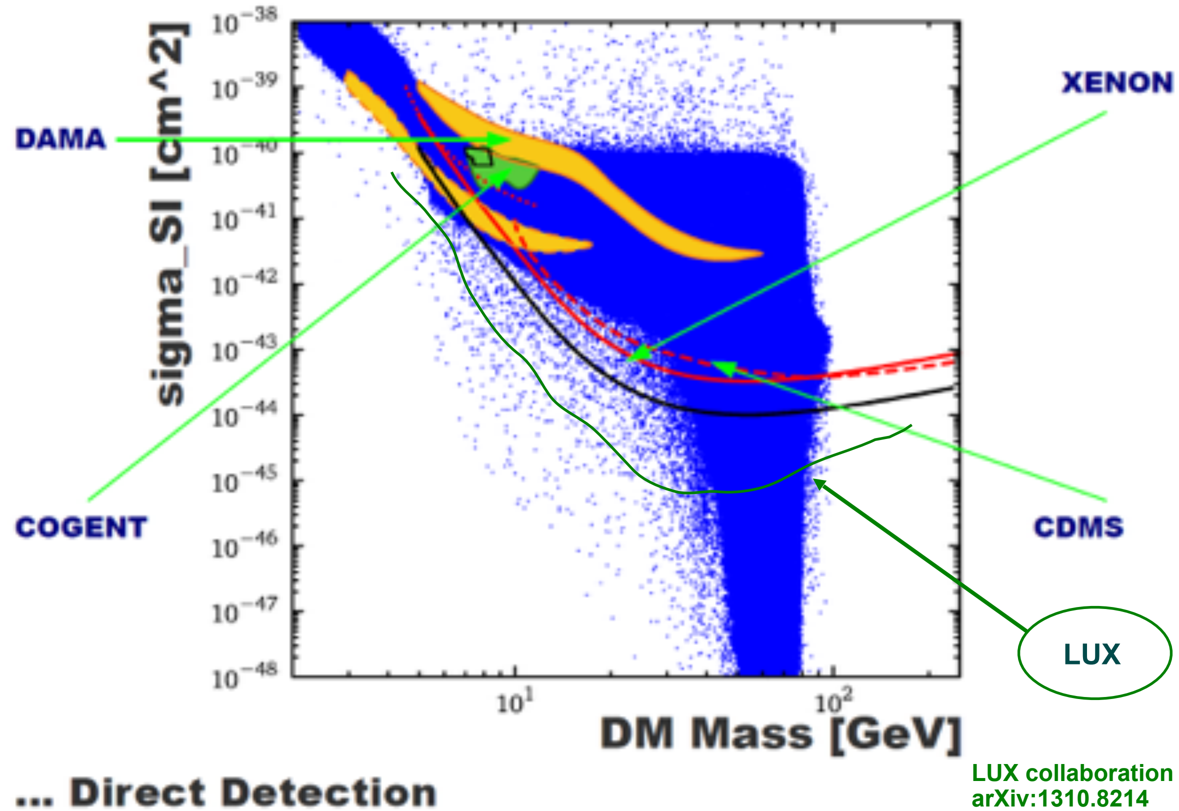
Dark Matter Stability

Relevant Diagrams



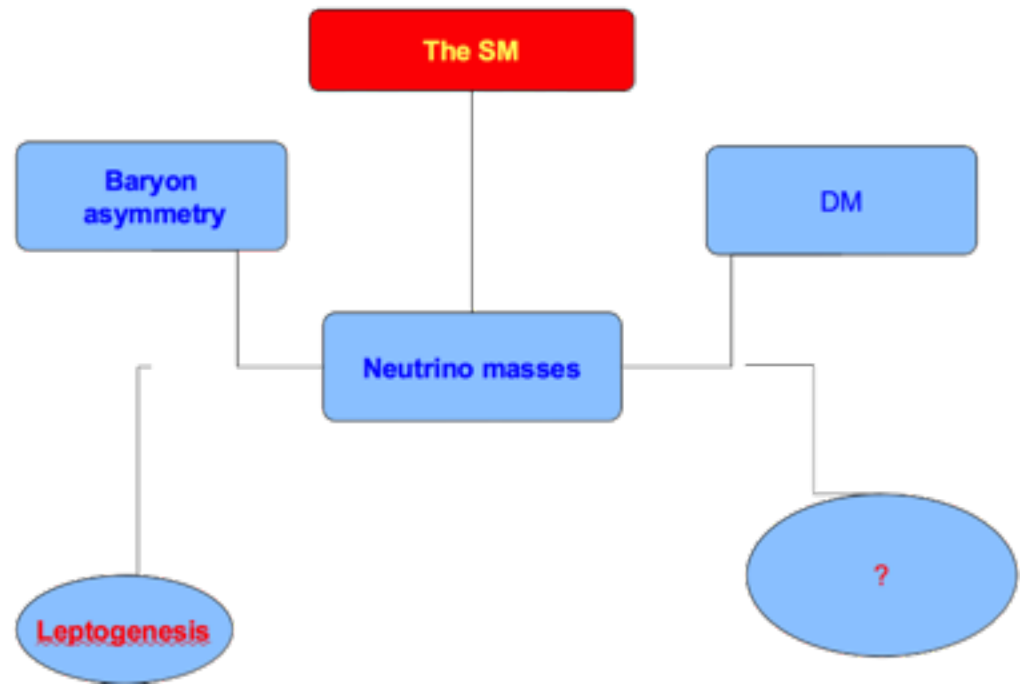
Boucenna, Hirsch, Morisi, Peinado, Taoso and Valle
JHEP 1105 (2011) 037

Direct detection



LUX collaboration
arXiv:1310.8214

The SM



Baryon asymmetry

The universe consists only on matter

$$\frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4. - 8.9) \times 10^{-11}$$

almost completely annihilated

$$n_B - n_{\bar{B}} \propto 1000000001 - 1000000000 = 1$$

Sakharov conditions

Sakharov's conditions for baryogenesis

1. B violation
2. Loss of thermal equilibrium
3. C, CP violation

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Sakharov's conditions for baryogenesis

1. B violation
2. Loss of thermal equilibrium
3. C, CP violation

$X \rightarrow Y + B$ $\qquad\qquad$ $Y + B \rightarrow X$

$$\Gamma(Y + B \rightarrow X) = \Gamma(X \rightarrow Y + B)$$

inverse process destroys B

Sakharov conditions

Sakharov's conditions for baryogenesis

1. B violation
2. Loss of thermal equilibrium
3. C, CP violation

$X \rightarrow Y + B$ **C:** $\Gamma(\bar{X} \rightarrow \bar{Y} + \bar{B}) = \Gamma(X \rightarrow Y + B)$

Sakharov conditions

Sakharov's conditions for baryogenesis

1. B violation
2. Loss of thermal equilibrium
3. C, CP violation

$$X \to q_L q_L, \qquad X \to q_R q_R$$

$$CP: \quad q_L \to \bar{q}_R \qquad\qquad C: \quad q_L \to \bar{q}_L$$

$$\Gamma(X \to q_L q_L) \neq \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L)$$

$$\Gamma(X \to q_L q_L) = \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R) \qquad \Gamma(X \to q_R q_R) = \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L)$$

$$\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) = \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R) + \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L)$$

BG in the SM

Kobayashi-Maskawa CP Violating phase

$$d_{CP} = \sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin\delta_{CP} \cdot (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

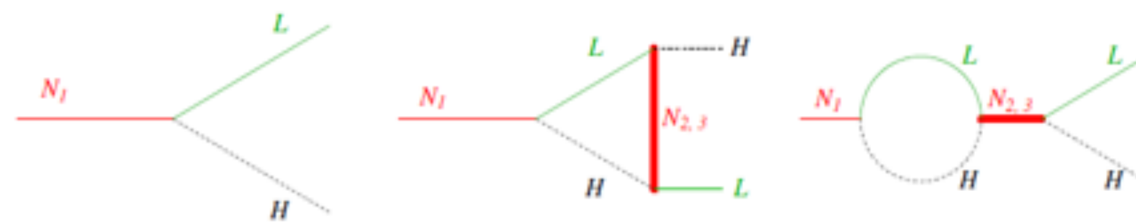
$$J = \det\left[m_u^2,\ m_d^2\right]$$

Shaposhnikov

$$\delta_{KM}^{CP} \sim \frac{J}{(100\ \mathrm{GeV})^{12}} \sim 10^{-20} \quad << \frac{n_B - \bar{n}_B}{n_B + \bar{n}_B} \sim \frac{n_B - \bar{n}_B}{s} = (8.4. - 8.9) \times 10^{-11}$$

This CP Violation Cannot be the Source of Baryon Asymmetry in The Universe

Leptogenesis



The simplest way to neutrino masses: Type I see-saw

Minkowski(1977),Yanagida(1979), Gell-Mann et al. (1979), Glashow (1980), Mohapatra and Senjanovic (1981, Schechter and Valle (1980)

$$-\mathcal{L}_{\rm seesaw} = \frac{1}{2} M_i \overline{N}_i N_i^c + \lambda_{\alpha i} \overline{l}_\alpha N_i \epsilon H^* \qquad m_\nu \simeq -\lambda M^{-1} \lambda^T \langle H \rangle^2$$

We get for **free**: baryogenesis through leptogenesis [Fukugita and Yanagida (1986)]

Conventional Type-I leptogenesis requires

$$M \gtrsim 10^9 \text{ GeV} \implies \lambda \sim 10^{-3}$$

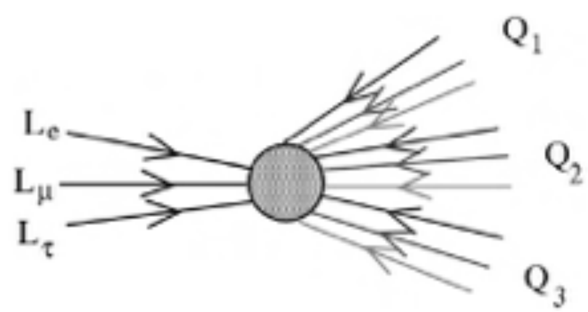
[Davidson and Ibarra (2002)]

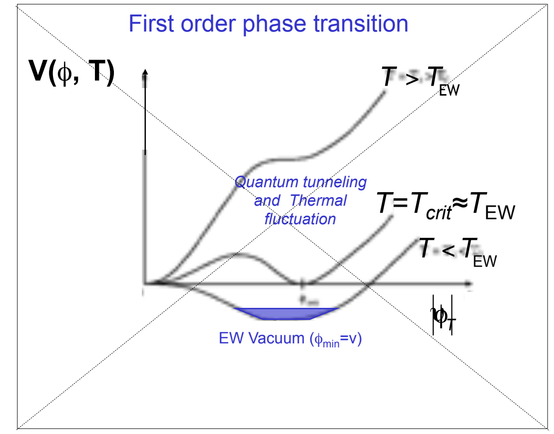
Resonant leptogenesis

[Pilaftsis (1997)]

$$M \sim 10^3 \text{ GeV} \implies \lambda \sim 10^{-6}$$

Leptogenesis





Klinkhamer and Manton

$$\Delta B = \Delta L = \pm 3$$

B-L conserved

Possible models

Type I see-saw

$$-\mathcal{L}_{\text{seesaw}} = \frac{1}{2} M_i \overline{N}_i N_i^c + \lambda_{\alpha i} \overline{\ell}_\alpha N_i \, \epsilon H^*$$

Possible models

Type I see-saw

$$-\mathcal{L}_{\text{seesaw}} = \frac{1}{2} M_i \overline{N}_i N_i^c + \lambda_{\alpha i} \overline{\ell}_\alpha N_i \epsilon H^*$$

New scalar that couple to **RH neutrino** and SM fermions $\tilde{\psi}$

$$-\mathcal{L}_{\tilde{\psi}} = \eta_{mi} \bar{\psi}_{Lm} N_i \tilde{\psi}$$

Possible models

Type I see-saw

$$-\mathcal{L}_{\text{seesaw}} = \frac{1}{2} M_i \overline{N}_i N_i^c + \lambda_{\alpha i} \overline{\ell}_\alpha N_i \, \epsilon H^*$$

New scalar that couple to **RH neutrino** and SM fermions $\tilde{\psi}$

$$-\mathcal{L}_{\tilde{\psi}} = \eta_{mi} \bar{\psi}_{Lm} N_i \, \tilde{\psi} + \sum_{\psi' \, \psi''} y_{mn} \bar{\psi}'_{Lm} \psi''_{Rn} \, \tilde{\psi} \; + \; \text{h.c.}$$

Possible models

Type I see-saw

$$-\mathcal{L}_{\text{seesaw}} = \frac{1}{2} M_i \overline{N}_i N_i^c + \lambda_{\alpha i} \bar{\ell}_\alpha N_i \, \epsilon H^*$$

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$\psi_L, \; \psi'_L$ (LH) fermion fields $\ell, \; e^c, \; Q, \; d^c, \; u^c$

ψ''_R RH fields $\ell^c, \; e, \; Q^c, \; d, \; u$

Possible models

Type I see-saw

$$-\mathcal{L}_{\text{seesaw}} = \frac{1}{2} M_i \overline{N}_i N_i^c + \lambda_{\alpha i} \bar{\ell}_\alpha N_i \,\epsilon H^*$$

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ψ_L, ψ'_L (LH) fermion fields $\ell,\, e^c,\, Q,\, d^c,\, u^c$

ψ''_R RH fields $\ell^c,\, e,\, Q^c,\, d,\, u$

$\tilde{\psi} = \tilde{\ell},\, \tilde{e},\, \tilde{Q},\, \tilde{d},\, \tilde{u}$

To match the gauge qn of ψ_L

Possible models

Type I see-saw

$$-\mathcal{L}_{\text{seesaw}} = \frac{1}{2} M_i \overline{N}_i N_i^c + \lambda_{\alpha i} \bar{\ell}_\alpha N_i \, \epsilon H^*$$

New scalar that couple to **RH neutrino** and SM fermions $\tilde{\psi}$

$$-\mathcal{L}_{\tilde{\psi}} = \eta_{mi} \bar{\psi}_{Lm} N_i \, \tilde{\psi} + \sum_{\psi' \, \psi''} y_{mn} \bar{\psi}'_{Lm} \psi''_{Rn} \, \tilde{\psi} \; + \text{ h.c.}$$

$\psi_L, \, \psi'_L$ (LH) fermion fields $\ell, \, e^c, \, Q, \, d^c, \, u^c$

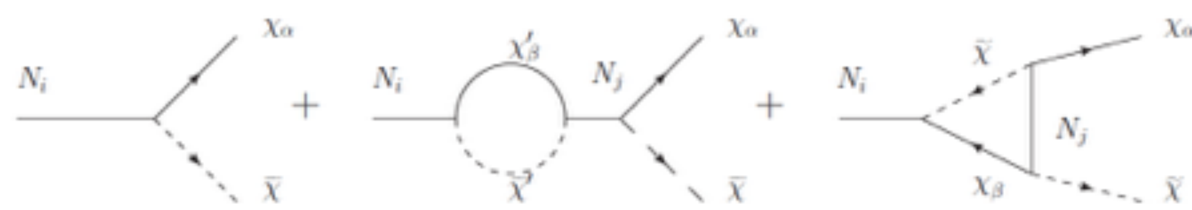
ψ''_R RH fields $\ell^c, \, e, \, Q^c, \, d, \, u$

$\tilde{\psi} = \tilde{\ell}, \, \tilde{e}, \, \tilde{Q}, \, \tilde{d}, \, \tilde{u}$ **ARE NOT SUPERPARTNERS** !!!!!!!

How does it works?

1. The production of RH neutrino through $\tilde{\psi}$ exchange which, being gauge non-singlets, have sizable couplings to the SM gauge bosons.
2. The new decay channel $N \to \bar{\tilde{\psi}}\tilde{\psi}$ with associated CP violating asymmetry contributions from self energy loops (λ and η), and from vertex corrections (λ).
3. They contribute via new self energy diagrams (λ) to the CP asymmetries in $N \to \bar{\ell}H$ decays.

Since the couplings η are not related to light neutrino masses, they can be sufficiently large to allow for N production with observable rates and for large enhancements of the CP asymmetries.



$\chi^{(\prime)} = \ell_\alpha,\ (\psi_m)$ and $\tilde{\chi}^{(\prime)} = H,\ (\tilde{\psi})$