

# *The current landscape of neutrino physics*

José W F Valle



<http://astroparticles.es/>

Laboratori Nazionali di Frascati - INFN, Feb 2015



VNIVERSITAT  
DE VALÈNCIA

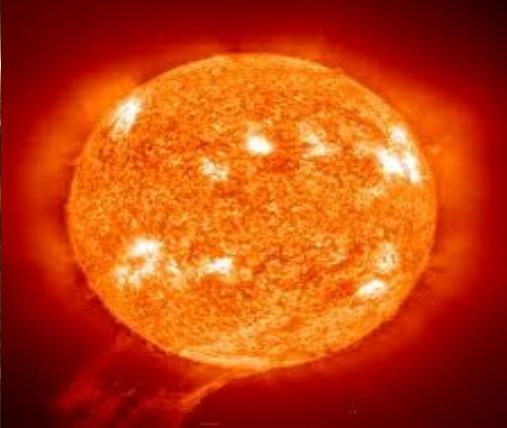
*Where do neutrinos come from?*

*336 / cm<sup>3</sup>: billions of  
Cosmic neutrinos  
Cross us every second*



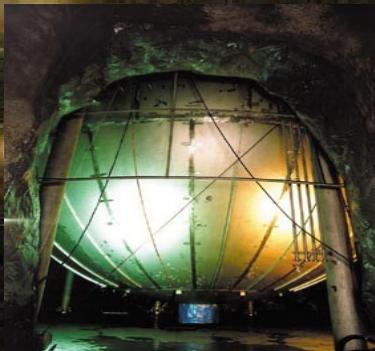
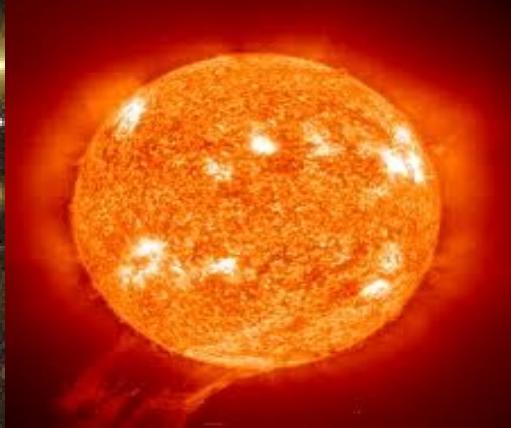
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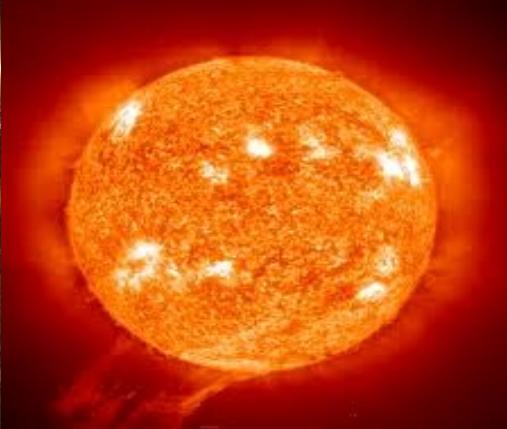
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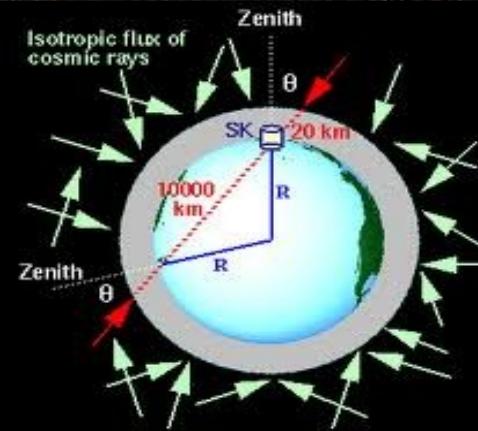
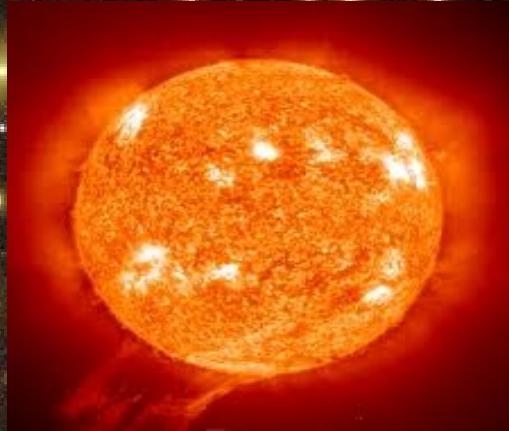


$$\theta_{12}$$

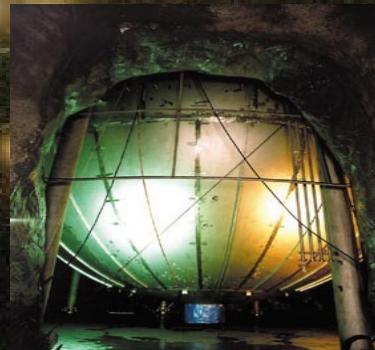


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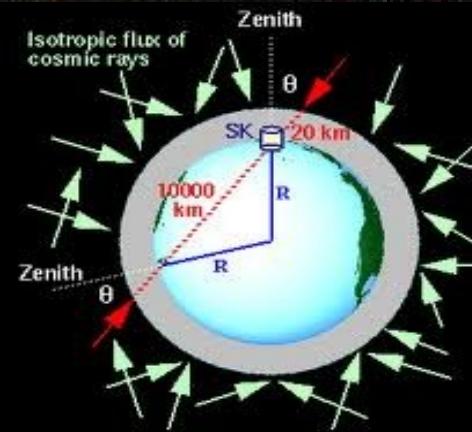
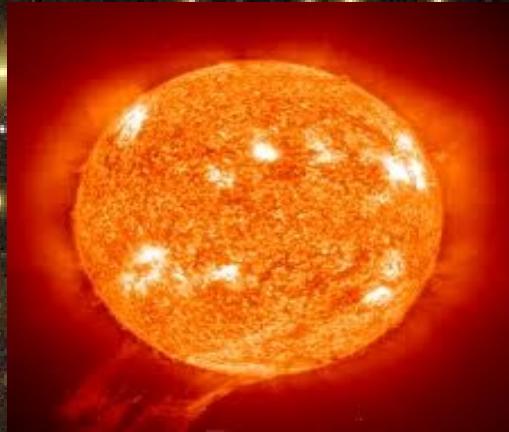


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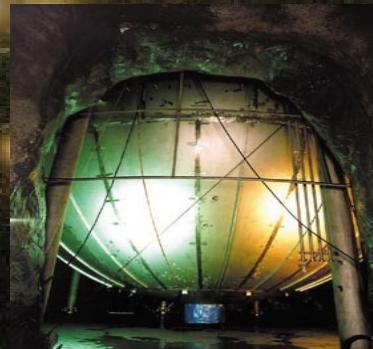
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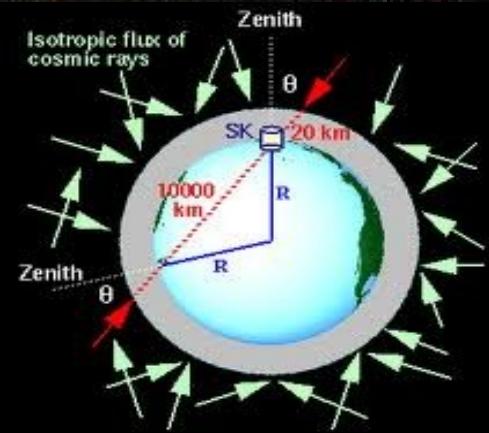
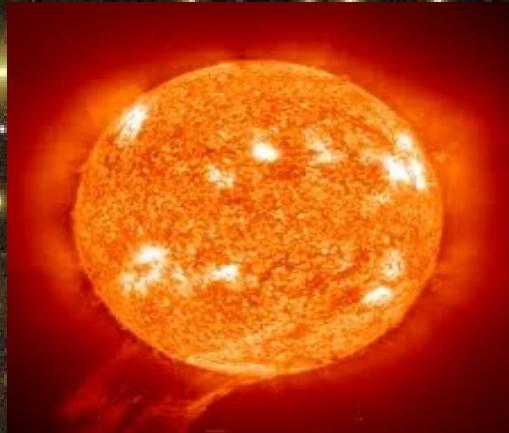
$$\theta_{12}$$

$$\theta_{23}$$



# Where do neutrinos come from?

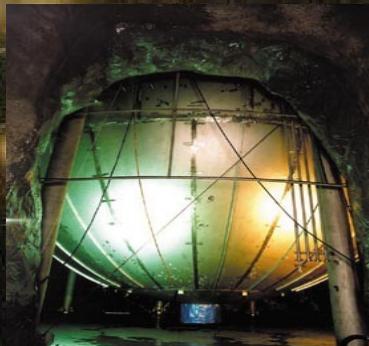
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$$\theta_{12}$$

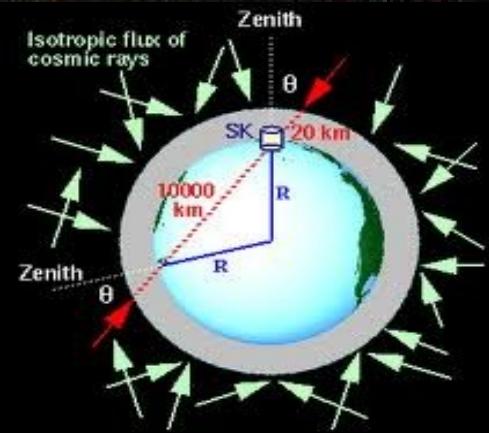
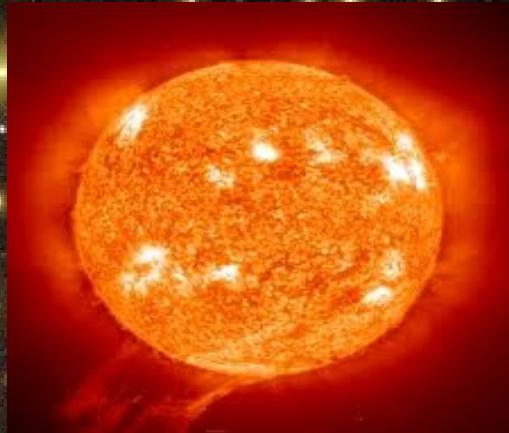
$$\theta_{23}$$

confirmed



# Where do neutrinos come from?

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$$\theta_{12}$$

$$\theta_{23}$$

$$\theta_{13}$$

$$\delta$$

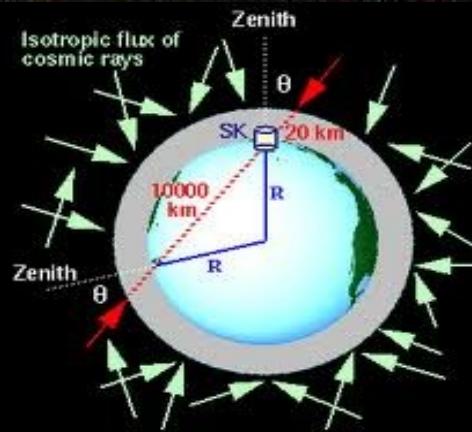
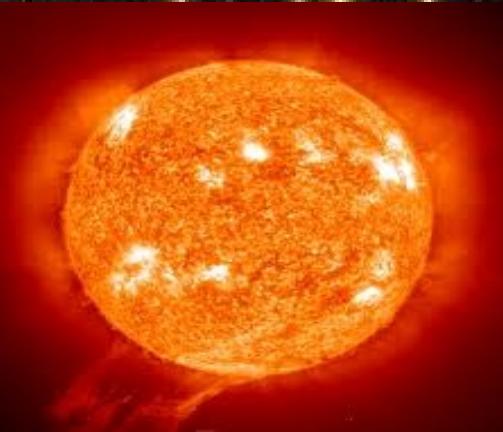
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Need  
to revise  
Standard  
model



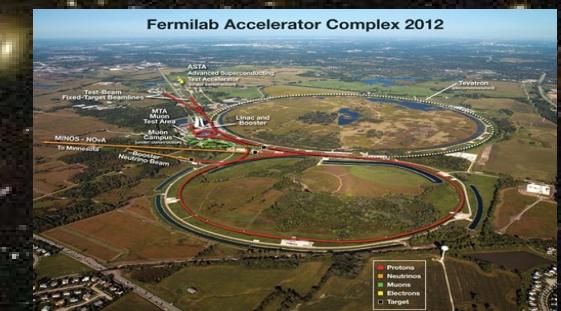
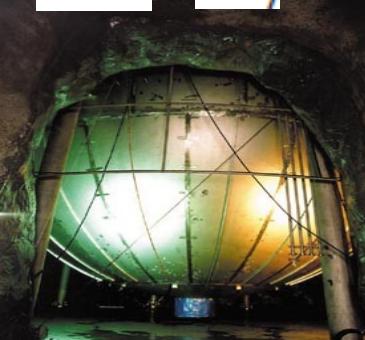
$$\theta_{12}$$

$$\theta_{13}$$

$$\theta_{23}$$

$$\delta$$

confirmed



# *The Standard Model*

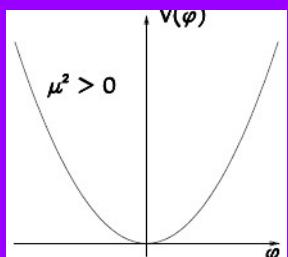
up to energies  $\sim 100$  GeV is the most precise theory of particle interactions we have

1968	$u$	1974	$c$	1995	$t$	1979	$g$
1968	$d$	1947	$s$	1977	$b$	1923	$\gamma$
1956	$\nu_e$	1962	$\nu_\mu$	2000	$\nu_\tau$	1983	$W$
1897	$e$	1937	$\mu$	1976	$\tau$	1983	$Z$

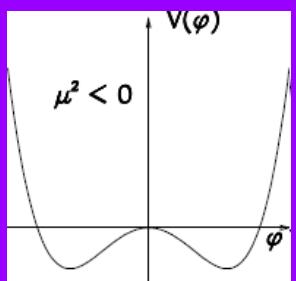
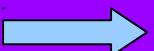
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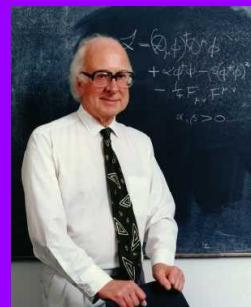
based on gauge principle  
and the Higgs mechanism



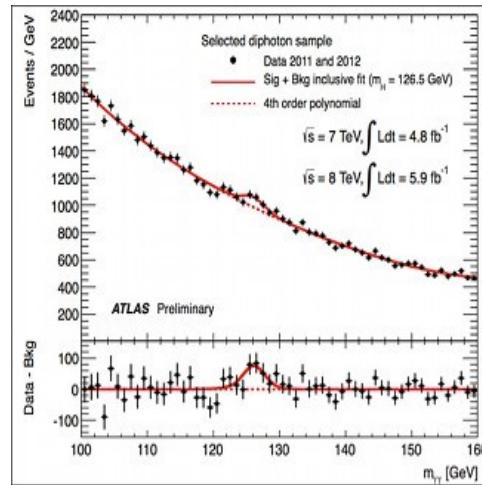
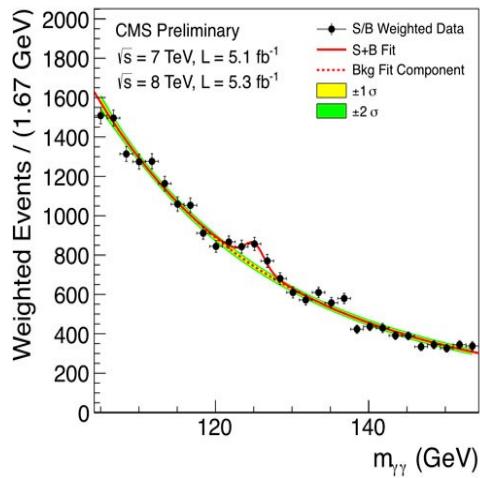
BEH



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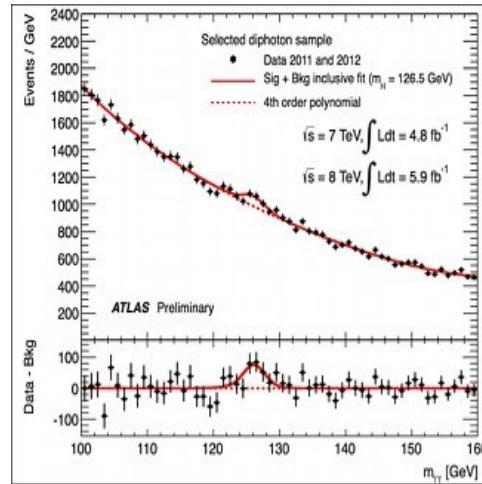
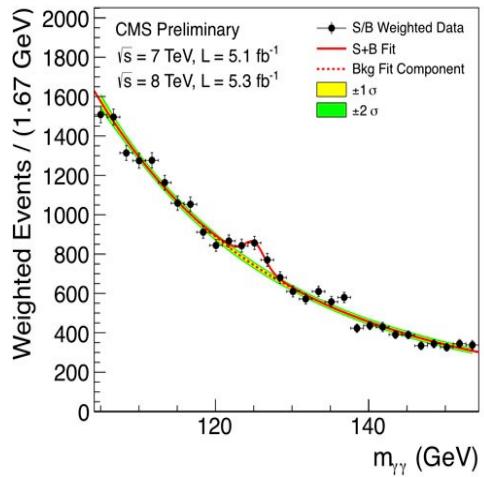


# *With the historic Higgs discovery*



SM complete

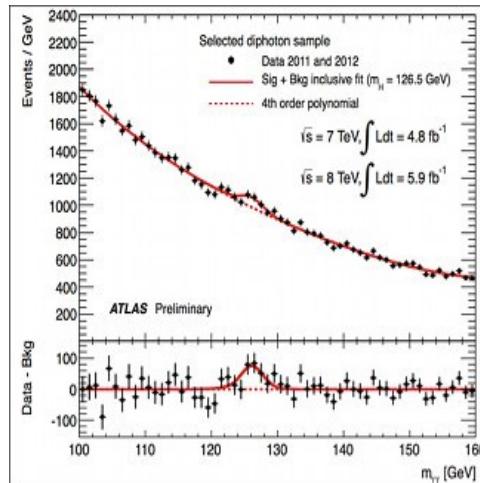
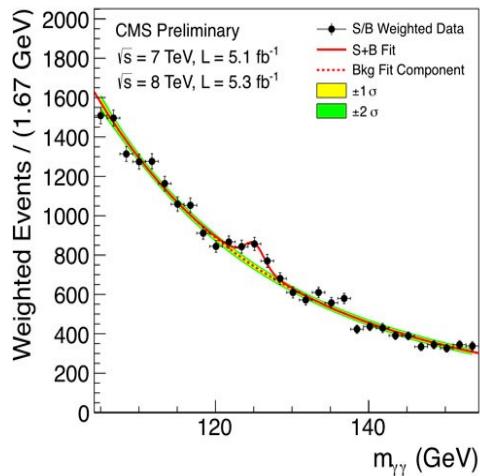
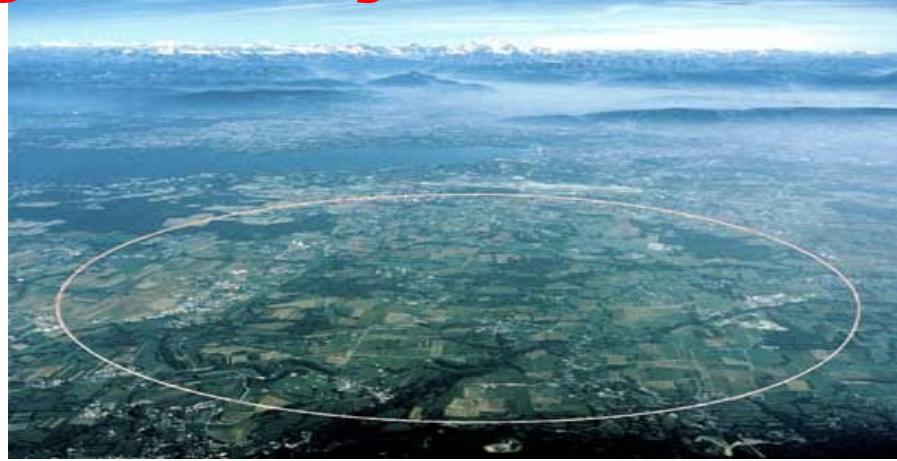
# *With the historic Higgs discovery*



complete  
were it not for  
neutrinos & cosmology



# *With the historic Higgs discovery*



complete  
were it not for  
neutrinos & cosmology

no neutrino masses  
no dark matter  
no baryon asymmetry  
no inflation



# *Neutrinos & Invisible Higgs*

$$\sigma = \frac{v_1}{\sqrt{2}} + \frac{R_1 + i I_1}{\sqrt{2}}$$

$$\phi^0 = \frac{v_2}{\sqrt{2}} + \frac{R_2 + i I_2}{\sqrt{2}}$$

<http://arxiv.org/abs/1502.01649>

# *Neutrinos & Invisible Higgs*

$$\Gamma(H_2 \rightarrow H_1 H_1) = \frac{g_{H_2 H_1 H_1}^2}{32\pi m_{H_2}} \left(1 - \frac{4m_{H_1}^2}{m_{H_2}^2}\right)^{1/2}$$

$$\Gamma(H_i \rightarrow J J) = \frac{1}{32\pi} \frac{g_{H_i J J}^2}{m_{H_i}}.$$

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channel	ATLAS	CMS
$\mu_{\gamma\gamma}$	$1.17 \pm 0.27$	$1.14^{+0.26}_{-0.23}$
$\mu_{WW}$	$1.00^{+0.32}_{-0.29}$	$0.83 \pm 0.21$
$\mu_{ZZ}$	$1.44^{+0.40}_{-0.35}$	$1.00 \pm 0.29$
$\mu_{\tau^+\tau^-}$	$1.4^{+0.5}_{-0.4}$	$0.91 \pm 0.27$
$\mu_{b\bar{b}}$	$0.2^{+0.7}_{-0.6}$	$0.93 \pm 0.49$

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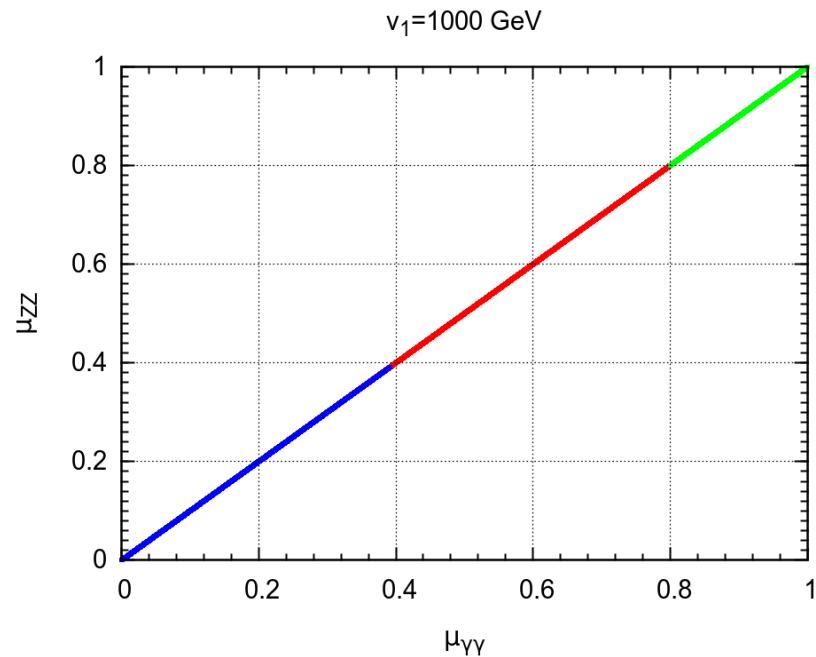
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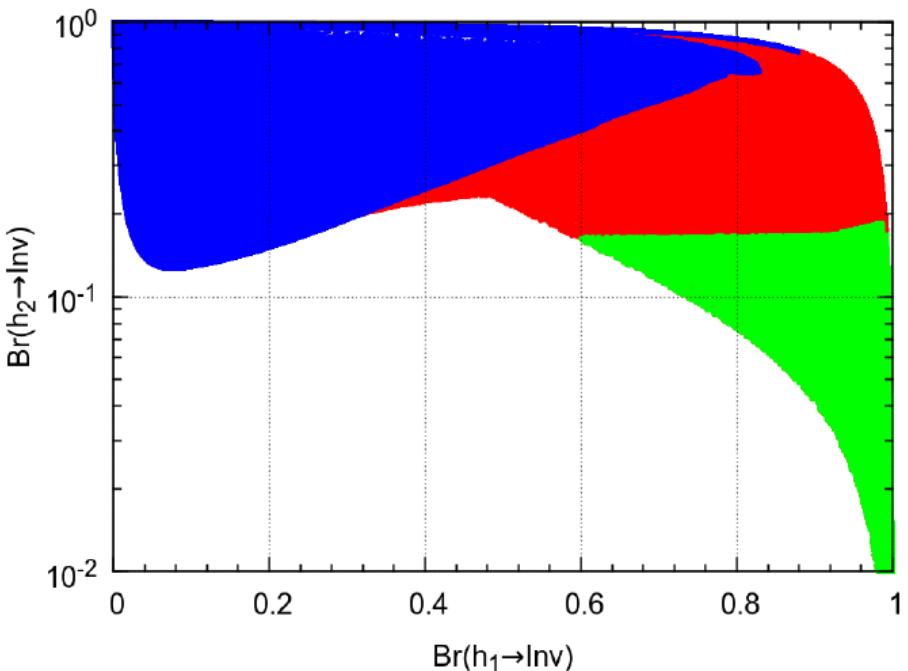


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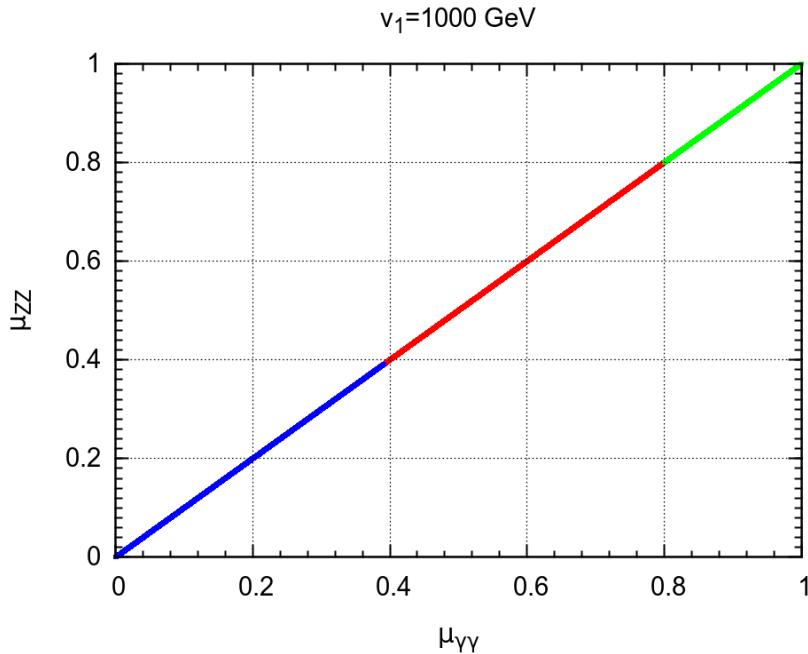
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$v_1=1000$  GeV



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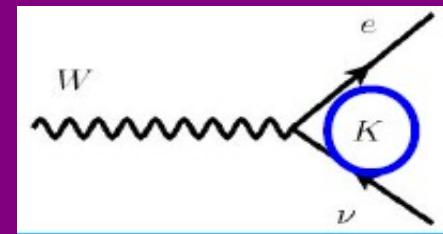
<http://arxiv.org/abs/1502.01649>



# LEPTONIC CKM MATRIX

$$K = \omega_{23} \cdot \omega_{13} \cdot \omega_{12}$$

Schechter & JV PRD22 (1980) 2227 & PDG  
Rodejohann, JV Phys.Rev. D84 (2011) 073011

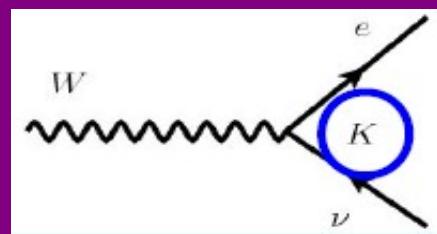


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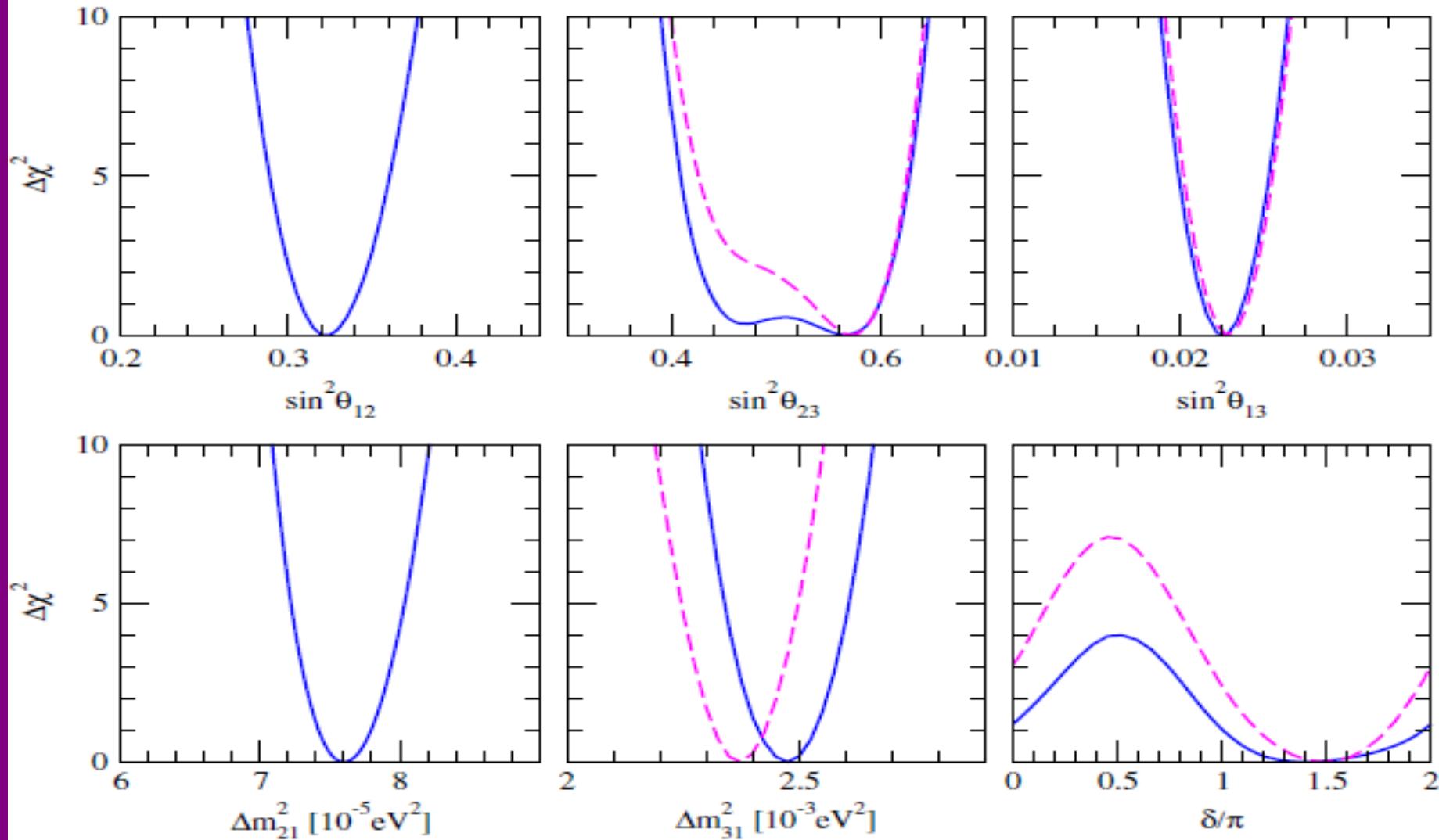
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Schechter & JV PRD22 (1980) 2227 & PDG

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PHYSICAL REVIEW D 90, 093006 (2014)



# THE ERA OF LEPTONIC CPV STARTS

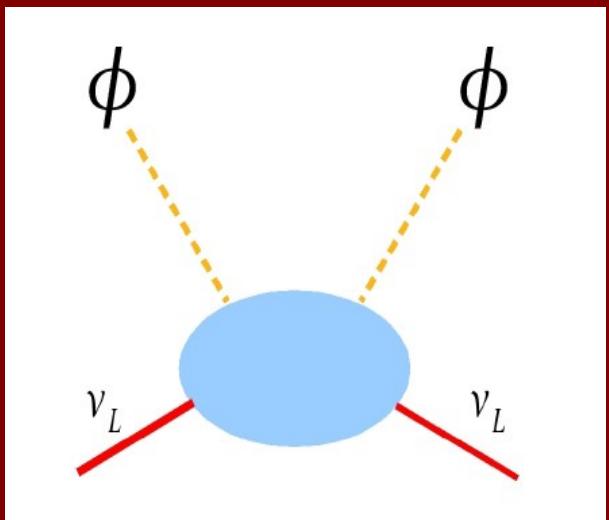
PHYSICAL REVIEW D 90, 093006 (2014)

TABLE II. Neutrino oscillation parameters summary from the global analysis updated after Neutrino 2014 conference.

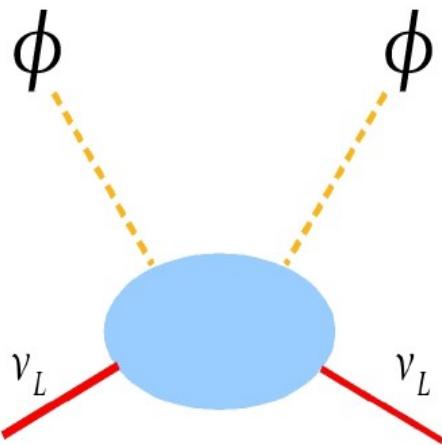
Parameter	Best fit $\pm 1\sigma$	$2\sigma$ range	$3\sigma$ range
$\Delta m_{21}^2 [10^{-5} \text{ eV}^2]$	$7.60^{+0.19}_{-0.18}$	7.26–7.99	7.11–8.18
$ \Delta m_{31}^2  [10^{-3} \text{ eV}^2]$ (NH)	$2.48^{+0.05}_{-0.07}$	2.35–2.59	2.30–2.65
$ \Delta m_{31}^2  [10^{-3} \text{ eV}^2]$ (IH)	$2.38^{+0.05}_{-0.06}$	2.26–2.48	2.20–2.54
$\sin^2 \theta_{12}/10^{-1}$	$3.23 \pm 0.16$	2.92–3.57	2.78–3.75
$\theta_{12}/^\circ$	$34.6 \pm 1.0$	32.7–36.7	31.8–37.8
$\sin^2 \theta_{23}/10^{-1}$ (NH)	$5.67^{+0.32a}_{-1.24}$	4.14–6.23	3.93–6.43
$\theta_{23}/^\circ$	$48.9^{+1.8}_{-7.2}$	40.0–52.1	38.8–53.3
$\sin^2 \theta_{23}/10^{-1}$ (IH)	$5.73^{+0.25}_{-0.39}$	4.35–6.21	4.03–6.40
$\theta_{23}/^\circ$	$49.2^{+1.5}_{-2.3}$	41.3–52.0	39.4–53.1
$\sin^2 \theta_{13}/10^{-2}$ (NH)	$2.26 \pm 0.12$	2.02–2.50	1.90–2.62
$\theta_{13}/^\circ$	$8.6^{+0.3}_{-0.2}$	8.2–9.1	7.9–9.3
$\sin^2 \theta_{13}/10^{-2}$ (IH)	$2.29 \pm 0.12$	2.05–2.52	1.93–2.65
$\theta_{13}/^\circ$	$8.7 \pm 0.2$	8.2–9.1	8.0–9.4
$\delta/\pi$ (NH)	$1.41^{+0.55}_{-0.40}$	0.0–0.2.0	0.0–2.0
$\delta/^\circ$	$254^{+99}_{-72}$	0–360	0–360
$\delta/\pi$ (IH)	$1.48 \pm 0.31$	0.00–0.09 & 0.86–2.0	0.0–2.0
$\delta/^\circ$	$266 \pm 56$	0–16 & 155–360	0–360

<sup>a</sup>There is a local minimum in the first octant, at  $\sin^2 \theta_{23} = 0.473$  with  $\Delta\chi^2 = 0.36$  with respect to the global minimum

# ORIGIN OF NEUTRINO MASS AND SEESAW



# *ORIGIN OF NEUTRINO MASS AND SEESAW*

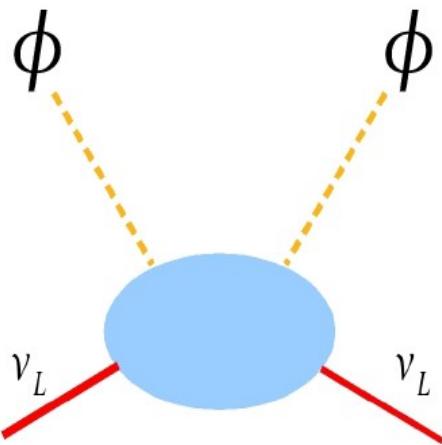


**SCALE**

**MECHANISM**

**FLAVOR STRUCTURE**

# *ORIGIN OF NEUTRINO MASS AND SEESAW*



**SCALE**

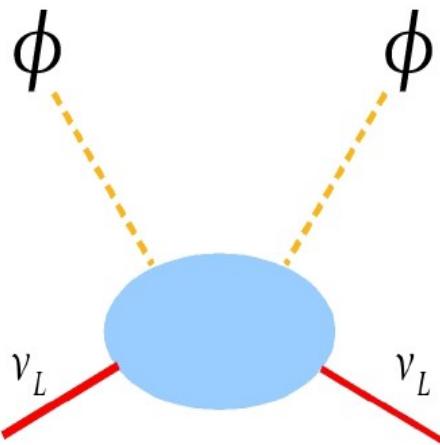
**MECHANISM**

**FLAVOR STRUCTURE**

$$v_3 v_1 \sim v_2^2 \text{ with } v_1 \gg v_2 \gg v_3$$



# *ORIGIN OF NEUTRINO MASS AND SEESAW*



fermion exchange  
**TYPE I**

Minkowski 77  
Gellman Ramond Slansky 80  
Glashow, Yanagida 79  
Mohapatra Senjanovic 80  
Lazarides Shafi Weterrick 81  
Schechter-Valle, 80 & 82

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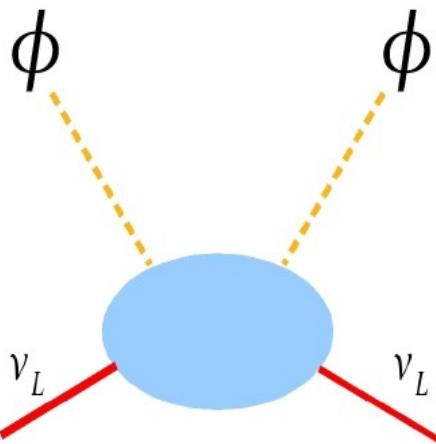


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Scalar-exchange  
**TYPE II**

Schechter-Valle 80/82



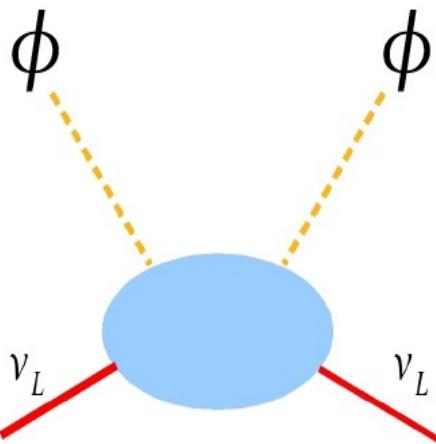
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$$v_3 v_1 \sim v_2^2 \text{ with } v_1 \gg v_2 \gg v_3$$

**MECHANISM**

**FLAVOR STRUCTURE**

# ORIGIN OF NEUTRINO MASS AND SEESAW

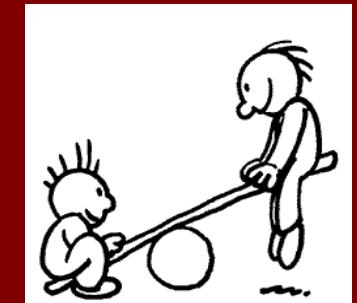


fermion exchange  
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**SCALE**

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**MECHANISM**

Number & properties of messengers

**FLAVOR STRUCTURE**

**LOW-SCALE SEESAW**

Mohapatra-Valle 86  
Akhmedov et al PRD53 (1996) 2752  
Malinsky et al PRL95(2005)161801  
Bazzocchi et al, PRD81 (2010) 051701

# Radiative neutrino mass in 331 scheme

# generations = # colours

Gauge vs Higgs

Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

TABLE I. Matter content of the model, where  $\hat{u}_R \equiv (u_R, c_R, t_R, t'_R)$  and  $\hat{d}_R \equiv (d_R, s_R, b_R, d'_R, s'_R)$  (see text).

	$\psi_L^\ell$	$\ell_R$	$Q_L^{1,2}$	$Q_L^3$	$\hat{u}_R$	$\hat{d}_R$	$S$	$\phi_1$	$\phi_2$	$\phi_3$
$SU(3)_c$	<b>1</b>	<b>1</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>
$SU(3)_L$	<b>3*</b>	<b>1</b>	<b>3</b>	<b>3*</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>3*</b>	<b>3*</b>	<b>3*</b>
$U(1)_X$	$-\frac{1}{3}$	-1	0	$+\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	0	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
$\mathcal{L}$	$-\frac{1}{3}$	-1	$-\frac{2}{3}$	$+\frac{2}{3}$	0	0	1	$+\frac{2}{3}$	$-\frac{4}{3}$	$+\frac{2}{3}$

# Radiative neutrino mass in 331 scheme

# generations = # colours

Gauge vs Higgs

Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

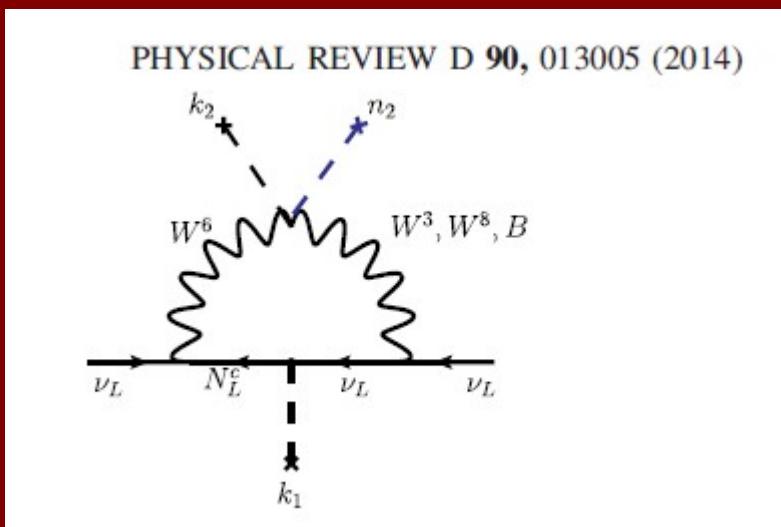


TABLE I. Matter content of the model, where  $\hat{u}_R \equiv (u_R, c_R, t_R, t'_R)$  and  $\hat{d}_R \equiv (d_R, s_R, b_R, d'_R, s'_R)$  (see text).

	$\psi_L^\ell$	$\ell_R$	$Q_L^{1,2}$	$Q_L^3$	$\hat{u}_R$	$\hat{d}_R$	$S$	$\phi_1$	$\phi_2$	$\phi_3$
$SU(3)_c$	<b>1</b>	<b>1</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>
$SU(3)_L$	<b>3*</b>	<b>1</b>	<b>3</b>	<b>3*</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>3*</b>	<b>3*</b>	<b>3*</b>
$U(1)_X$	$-\frac{1}{3}$	-1	0	$+\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	0	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
$\mathcal{L}$	$-\frac{1}{3}$	-1	$-\frac{2}{3}$	$+\frac{2}{3}$	0	0	1	$+\frac{2}{3}$	$-\frac{4}{3}$	$+\frac{2}{3}$

$$\langle \phi_1 \rangle = \begin{bmatrix} \left( \begin{array}{c} k_1 \\ 0 \\ 0 \end{array} \right) \end{bmatrix}, \quad \langle \phi_2 \rangle = \begin{bmatrix} \left( \begin{array}{c} 0 \\ 0 \\ n_1 \end{array} \right) \end{bmatrix}, \quad \langle \phi_3 \rangle = \begin{bmatrix} \left( \begin{array}{c} 0 \\ k_2 \\ n_2 \end{array} \right) \end{bmatrix}$$

# Radiative neutrino mass in 331 scheme

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Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

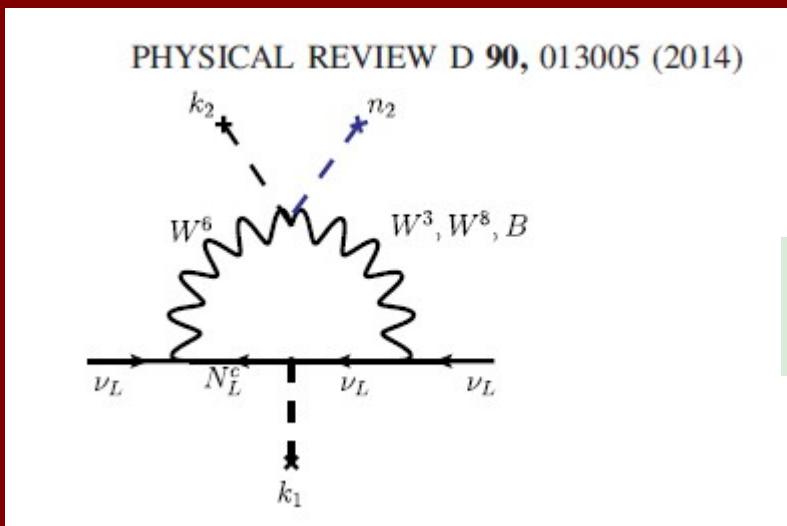


TABLE I. Matter content of the model, where  $\hat{u}_R \equiv (u_R, c_R, t_R, t'_R)$  and  $\hat{d}_R \equiv (d_R, s_R, b_R, d'_R, s'_R)$  (see text).

	$\psi_L^\ell$	$\ell_R$	$Q_L^{1,2}$	$Q_L^3$	$\hat{u}_R$	$\hat{d}_R$	$S$	$\phi_1$	$\phi_2$	$\phi_3$
$SU(3)_c$	<b>1</b>	<b>1</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>
$SU(3)_L$	<b>3*</b>	<b>1</b>	<b>3</b>	<b>3*</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>3*</b>	<b>3*</b>	<b>3*</b>
$U(1)_X$	$-\frac{1}{3}$	-1	0	$+\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	0	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
$\mathcal{L}$	$-\frac{1}{3}$	-1	$-\frac{2}{3}$	$+\frac{2}{3}$	0	0	1	$+\frac{2}{3}$	$-\frac{4}{3}$	$+\frac{2}{3}$

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$$m_{\nu_{\text{light}}} \simeq \frac{g^2 \epsilon \beta}{16\pi^2} M_D \frac{m_{Z'}^2}{M_D^2 + m_{Z'}^2} \log \frac{m_{Z'}^2}{M_D^2}$$

$$\epsilon \sim \frac{k_2 n_2}{n_1^2 + n_2^2} \ll 1, \quad \beta \simeq m_D/M \ll 1$$

# Radiative neutrino mass in 331 scheme

# generations = # colours

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Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

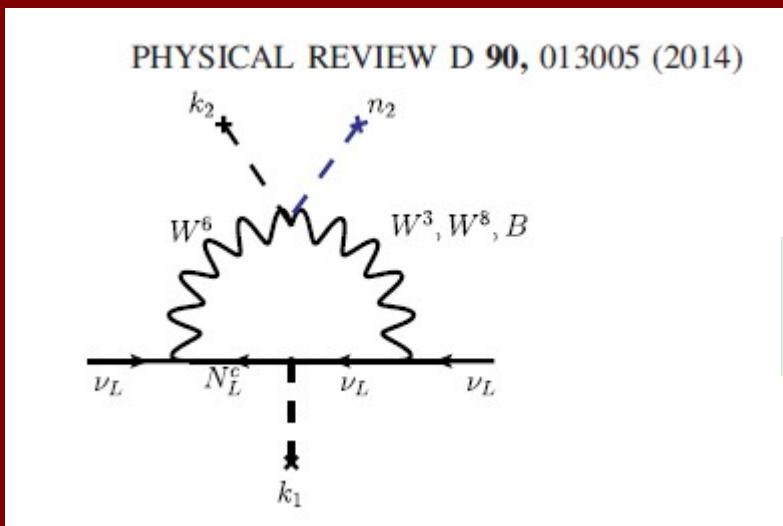


TABLE I. Matter content of the model, where  $\hat{u}_R \equiv (u_R, c_R, t_R, t'_R)$  and  $\hat{d}_R \equiv (d_R, s_R, b_R, d'_R, s'_R)$  (see text).

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$SU(3)_c$	<b>1</b>	<b>1</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>
$SU(3)_L$	<b>3*</b>	<b>1</b>	<b>3</b>	<b>3*</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>3*</b>	<b>3*</b>	<b>3*</b>
$U(1)_X$	$-\frac{1}{3}$	-1	0	$+\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	0	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
$\mathcal{L}$	$-\frac{1}{3}$	-1	$-\frac{2}{3}$	$+\frac{2}{3}$	0	0	1	$+\frac{2}{3}$	$-\frac{4}{3}$	$+\frac{2}{3}$

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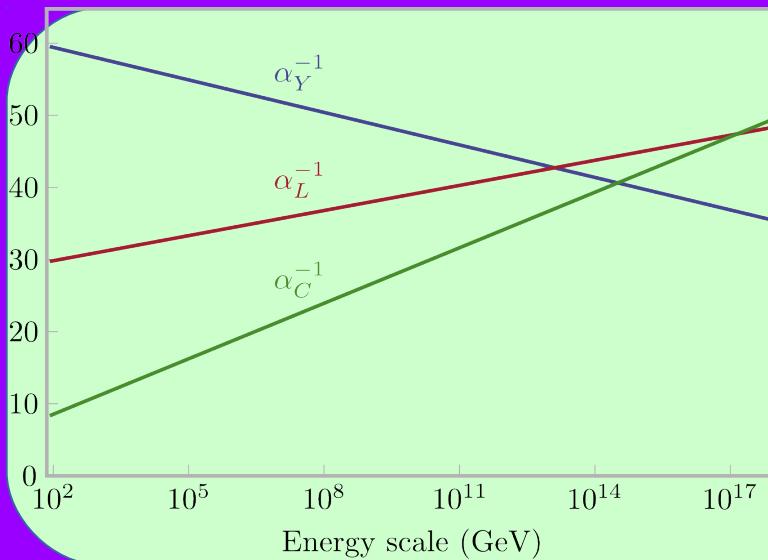
$$m_{\nu_{\text{light}}} \simeq \frac{g^2 \epsilon \beta}{16\pi^2} M_D \frac{m_{Z'}^2}{M_D^2 + m_{Z'}^2} \log \frac{m_{Z'}^2}{M_D^2}$$

$$\epsilon \sim \frac{k_2 n_2}{n_1^2 + n_2^2} \ll 1, \quad \beta \simeq m_D/M \ll 1$$

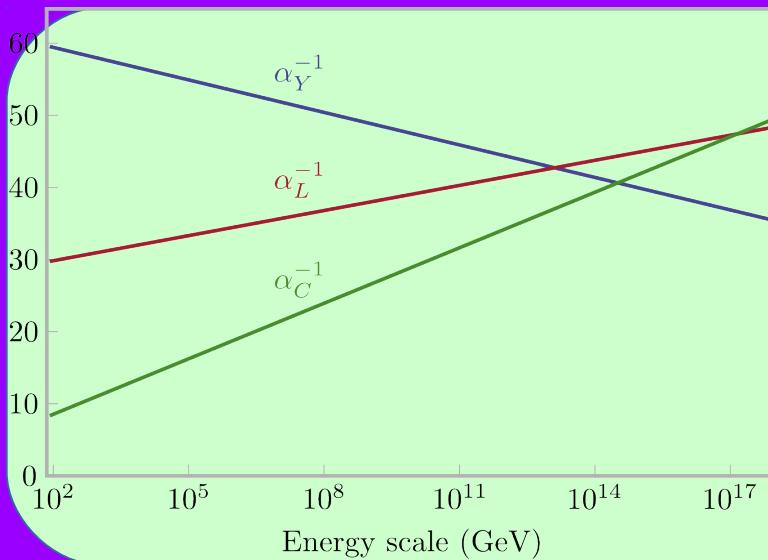
many other low-scale neutrino mass schemes ...

arXiv:1404.3751

# *gauge coupling unification : a near miss in SM?*

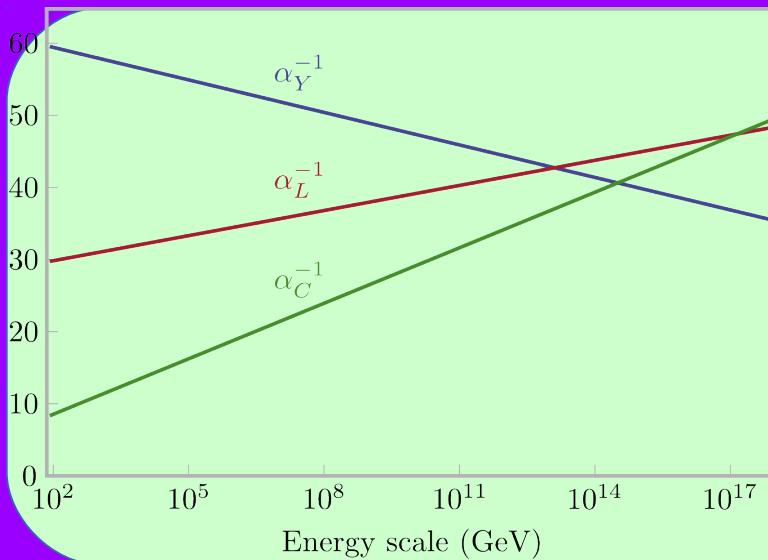


# *gauge coupling unification : a near miss in SM?*



What makes the gauge couplings unify? - A GUT (p decay)

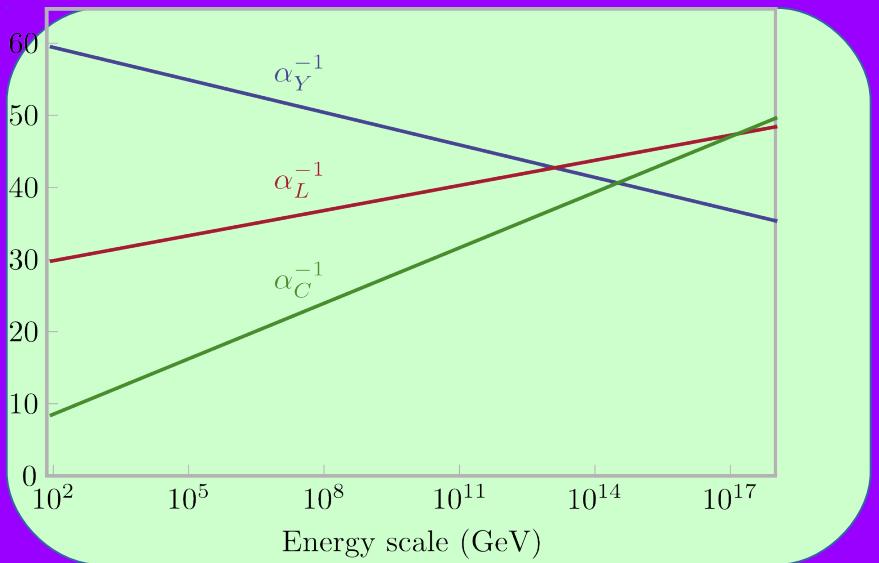
# *gauge coupling unification : a near miss in SM?*



**What makes the gauge couplings unify?**

- A GUT (p decay)
- SUSY (LHC-II)

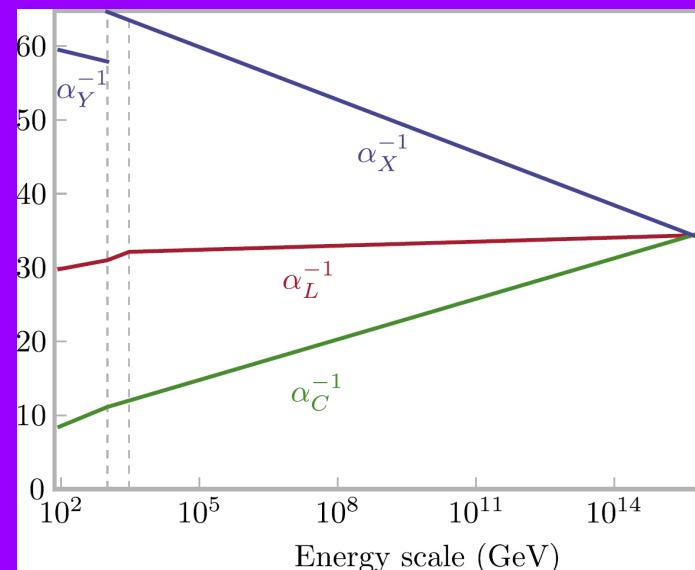
# *gauge coupling unification : a near miss in SM?*



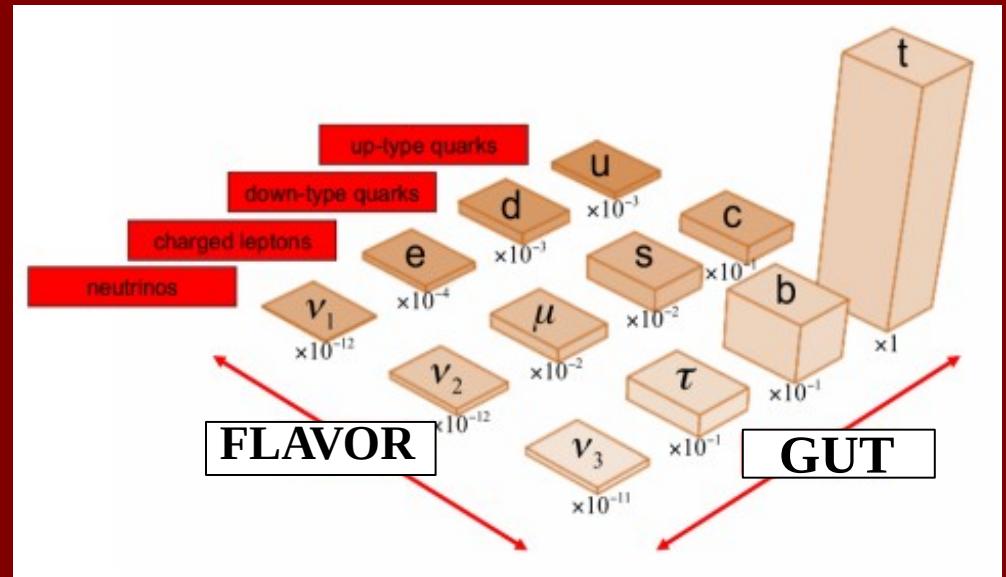
- What makes the gauge couplings unify?
- A GUT (p decay)
  - SUSY (LHC-II)
  - NEUTRINO PHYSICS

The physics responsible for gauge coupling unification may also induce small neutrino masses

Boucenna, Fonseca, Gonzalez-Canales, JV arXiv:1411.0566

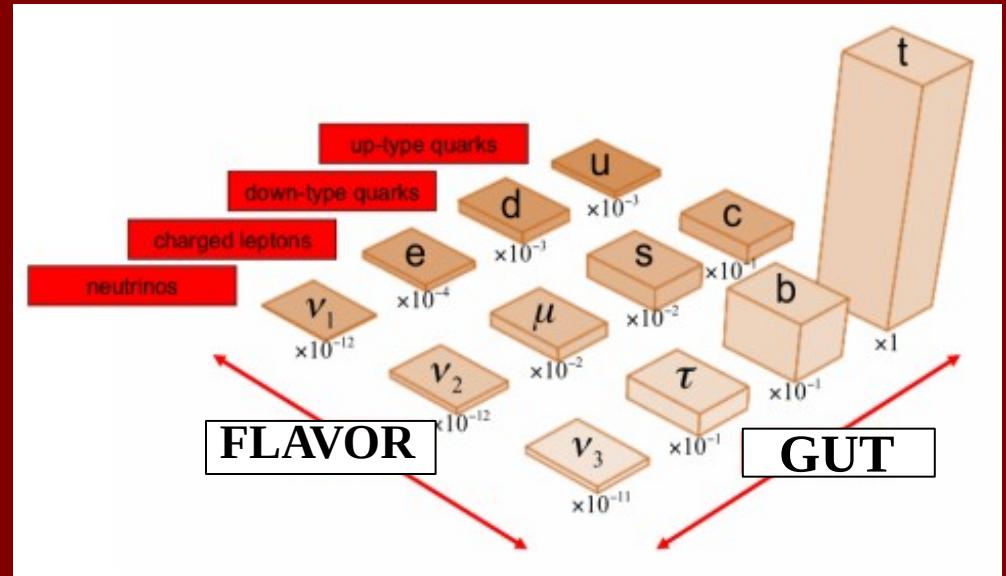


# Order in the chaos?



*Flavor symmetries have the potential of relating  $Q$  &  $L$  masses ...*

# Order in the chaos?

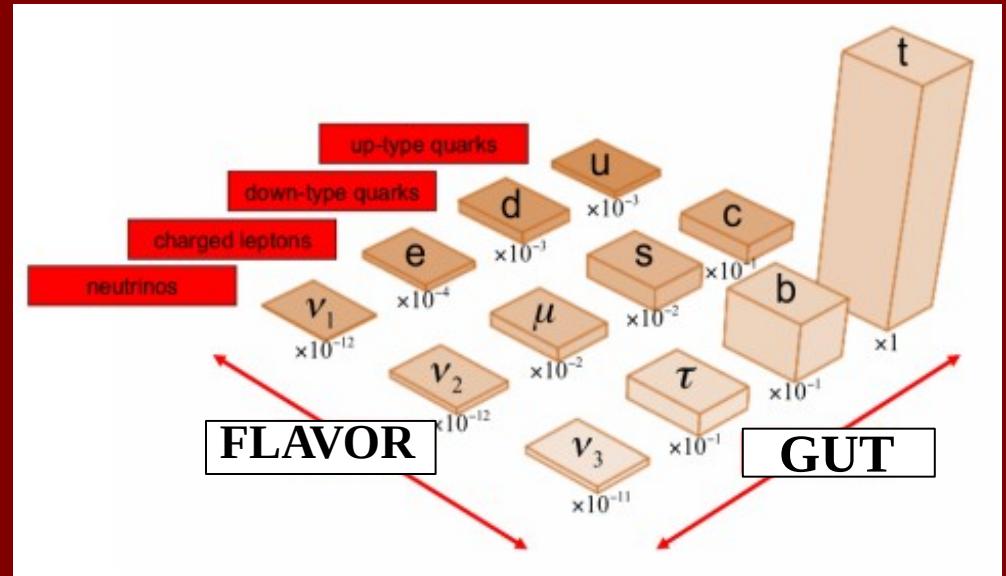


*Flavor symmetries have the potential of relating Q & L masses ...*

$$\frac{m_\tau}{\sqrt{m_e m_\mu}} \approx \frac{m_b}{\sqrt{m_d m_s}},$$

Morisi et al Phys.Rev. D84 (2011) 036003

# Order in the chaos?

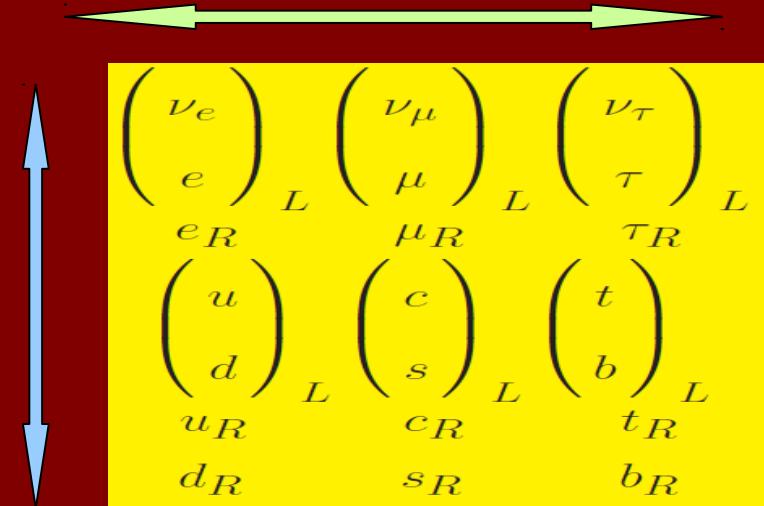


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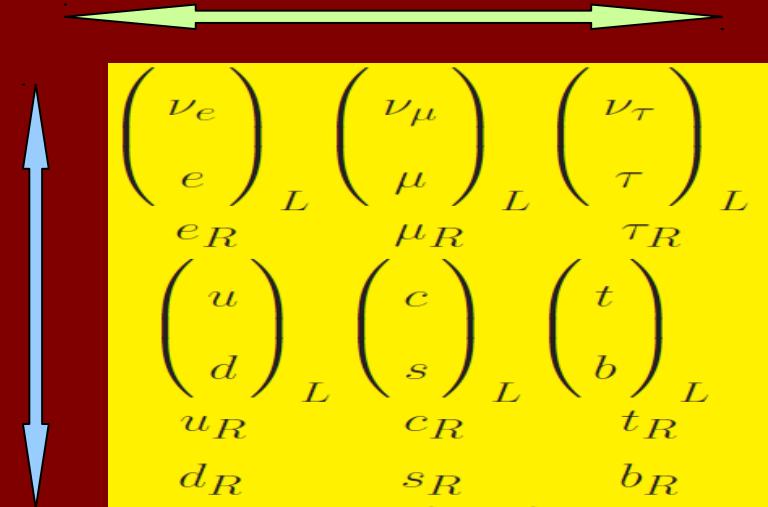
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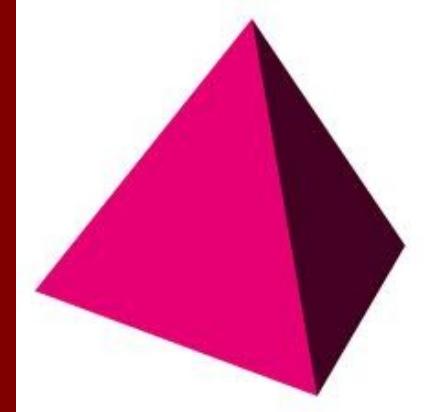
- |               |                             |
|---------------|-----------------------------|
| King et al    | Phys. Lett. B 724 (2013) 68 |
| Morisi et al  | Phys.Rev. D88 (2013) 036001 |
| Bonilla et al | Phys.Lett. B742 (2015) 99   |



# FLAVOR SYMMETRY



# FLAVOR SYMMETRY



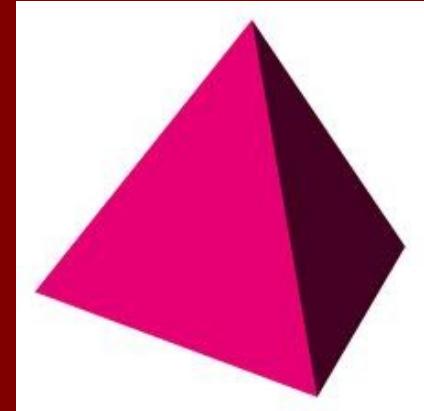
Babu-Ma-Valle PLB552 (2003) 207  
 Hirsch et al PRD69 (2004) 093006

$$\sin^2 \theta_{23} = 0.5$$

$$\sin^2 \theta_{13} = 0$$

$\begin{pmatrix} \nu_e \\ e \\ e_R \\ u \\ d \\ u_R \\ d_R \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \\ \mu_R \\ c \\ s \\ c_R \\ s_R \end{pmatrix}_L$
$\begin{pmatrix} \nu_\tau \\ \tau \\ \tau_R \\ t \\ b \\ t_R \\ b_R \end{pmatrix}_L$	

# FLAVOR SYMMETRY



Babu-Ma-Valle PLB552 (2003) 207  
 Hirsch et al PRD69 (2004) 093006

$$\sin^2 \theta_{23} = 0.5 \quad \sin^2 \theta_{13} = 0$$

## Tri-Bimaximal ansatz

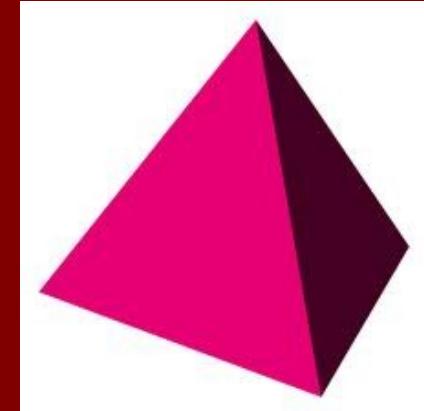
Harrison, Perkins, Scott 2000

$$U_{\text{TBM}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

(CP assumed)

$$\begin{array}{c}
 \left( \begin{array}{c} \nu_e \\ e \end{array} \right)_L \left( \begin{array}{c} \nu_\mu \\ \mu \end{array} \right)_L \left( \begin{array}{c} \nu_\tau \\ \tau \end{array} \right)_L \\
 \left( \begin{array}{c} e_R \\ \nu_e \end{array} \right) \left( \begin{array}{c} \mu_R \\ \nu_\mu \end{array} \right) \left( \begin{array}{c} \tau_R \\ \nu_\tau \end{array} \right) \\
 \left( \begin{array}{c} u \\ d \end{array} \right)_L \left( \begin{array}{c} c \\ s \end{array} \right)_L \left( \begin{array}{c} t \\ b \end{array} \right)_L \\
 \left( \begin{array}{c} u_R \\ \nu_u \end{array} \right) \left( \begin{array}{c} c_R \\ \nu_c \end{array} \right) \left( \begin{array}{c} t_R \\ \nu_t \end{array} \right) \\
 \left( \begin{array}{c} d_R \\ \nu_d \end{array} \right) \left( \begin{array}{c} s_R \\ \nu_s \end{array} \right) \left( \begin{array}{c} b_R \\ \nu_b \end{array} \right)
 \end{array}$$

# FLAVOR SYMMETRY



Babu-Ma-Valle PLB552 (2003) 207  
 Hirsch et al PRD69 (2004) 093006

$$\sin^2 \theta_{23} = 0.5 \quad \sin^2 \theta_{13} = 0$$

## Tri-Bimaximal ansatz

Altarelli, Feruglio 2005

$$\sin^2 \theta_{12} = 1/3$$

Harrison, Perkins, Scott 2000

$$U_{\text{TBM}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

(CP assumed)



**Gflavor**

FLASY  
2011, 2012,  
2013, 2014,  
2015 Jun29-Jul2



**Gflavor**

***Deviation  
of TBM***

Ishimori.etal ProgTheor  
Phys Suppl 183 (2010) 1

Holthausen et al 1212.2411

**Gflavor**

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Phys Suppl 183 (2010) 1

Holthausen et al 1212.2411

***change  
ansatz:***

Albright,Dueck,Rodejohann  
1004.2798

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1004.2798

**Abelian**

Ding, Morisi, JV PRD87 (2013) 1211.6506  
Boucenna,M,Tortola, JV  
PRD86 (2012) 051301



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Ishimori.etal ProgTheor  
Phys Suppl 183 (2010) 1

Holthausen et al 1212.2411

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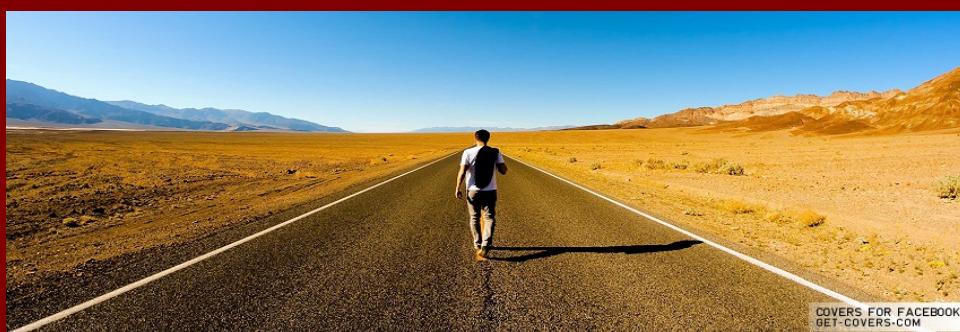
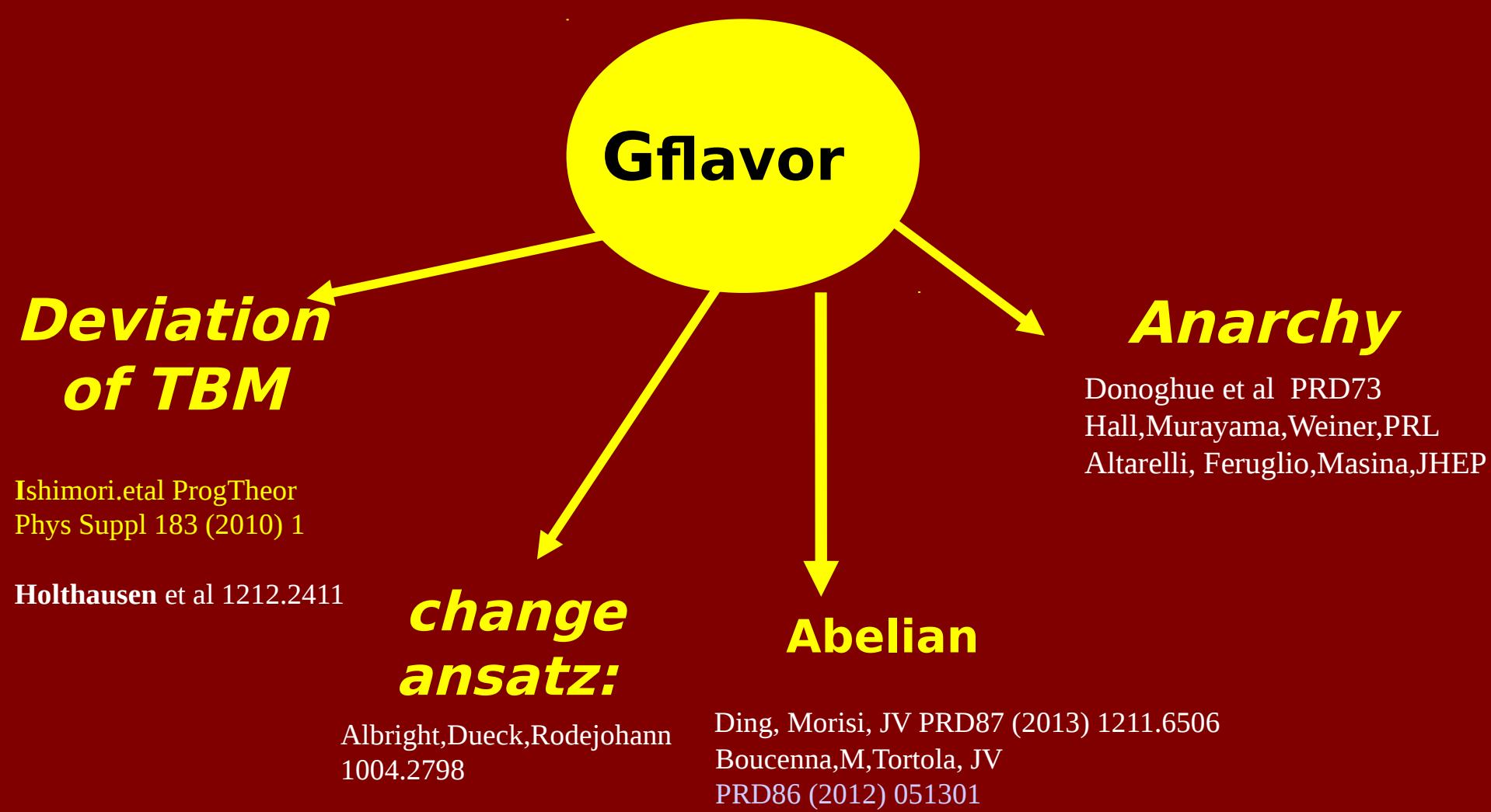
Albright,Dueck,Rodejohann  
1004.2798

***Anarchy***

Donoghue et al PRD73  
Hall,Murayama,Weiner,PRL  
Altarelli, Feruglio,Masina,JHEP

**Abelian**

Ding, Morisi, JV PRD87 (2013) 1211.6506  
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PRD86 (2012) 051301

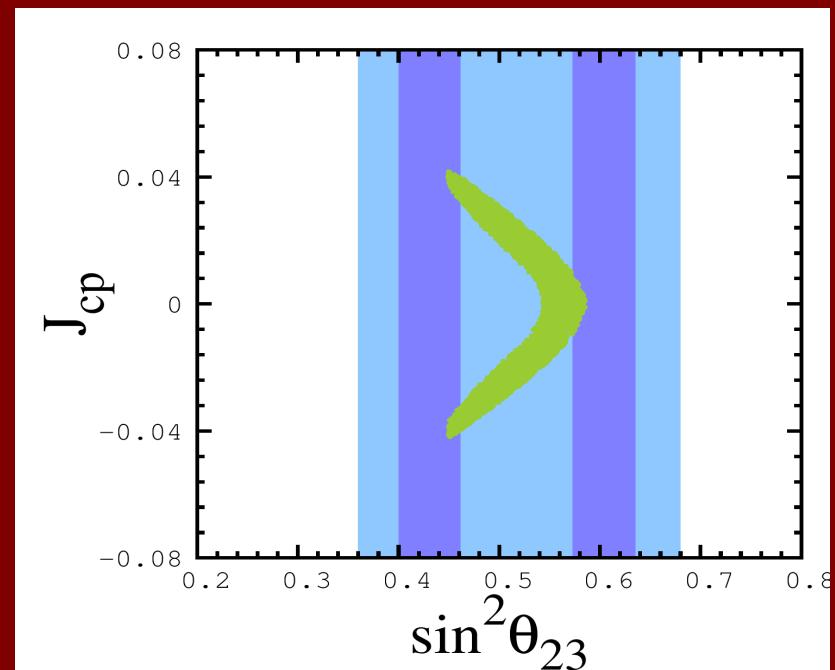


**Flavor roadmap**  
Fortsch.Phys. 61 (2013) 466-492

PHYSICAL REVIEW D 88, 016003 (2013)

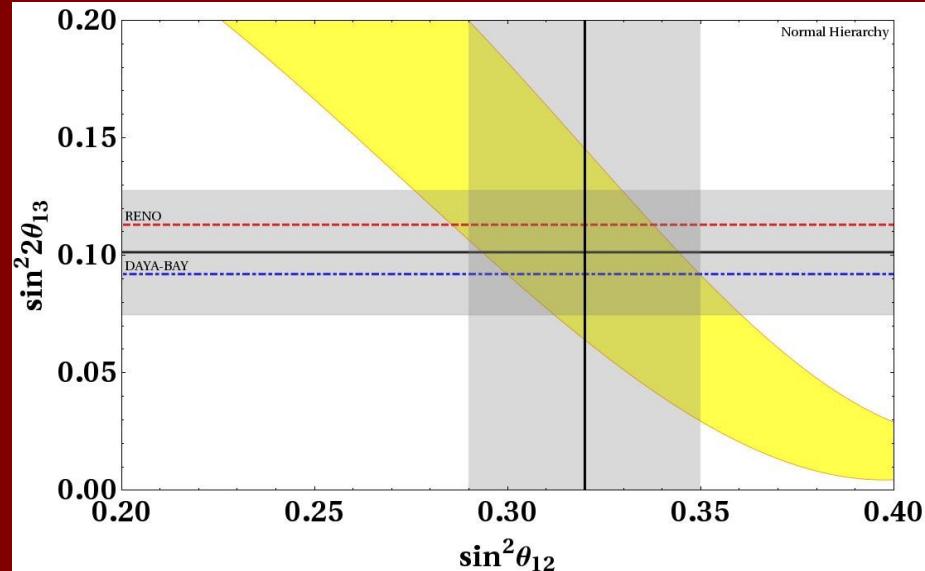
**Neutrino mixing with revamped  $A_4$  flavor symmetry**D. V. Forero,<sup>1,2,\*</sup> S. Morisi,<sup>3,†</sup> J. C. Romão,<sup>1,‡</sup> and J. W. F. Valle<sup>2,§</sup>

PHYSICAL REVIEW D 88, 016003 (2013)

**Neutrino mixing with revamped  $A_4$  flavor symmetry**D. V. Forero,<sup>1,2,\*</sup> S. Morisi,<sup>3,†</sup> J. C. Romão,<sup>1,‡</sup> and J. W. F. Valle<sup>2,§</sup>**STRIKING CORRELATION**

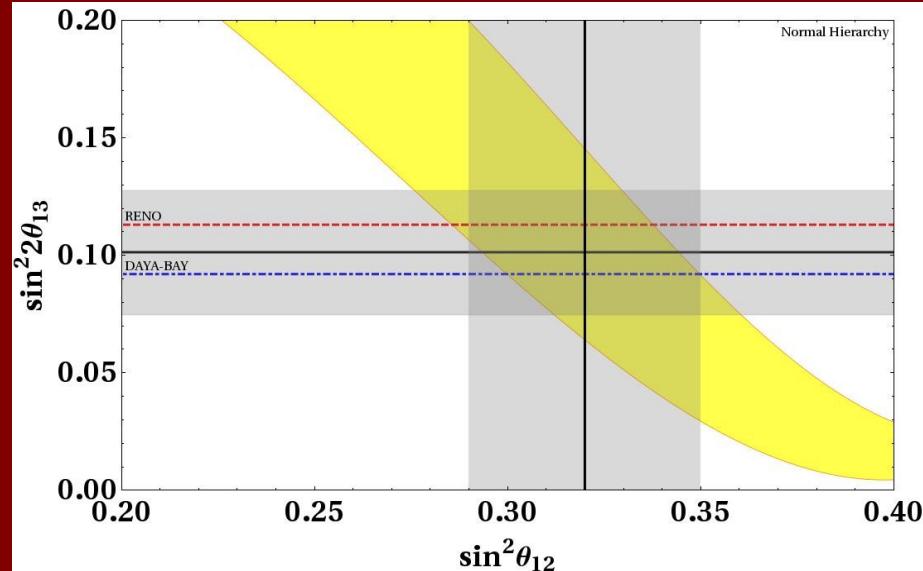
# OSCILLATION PARAMETER CORRELATIONS

Boucenna et al  
PhysRevD.86.073008

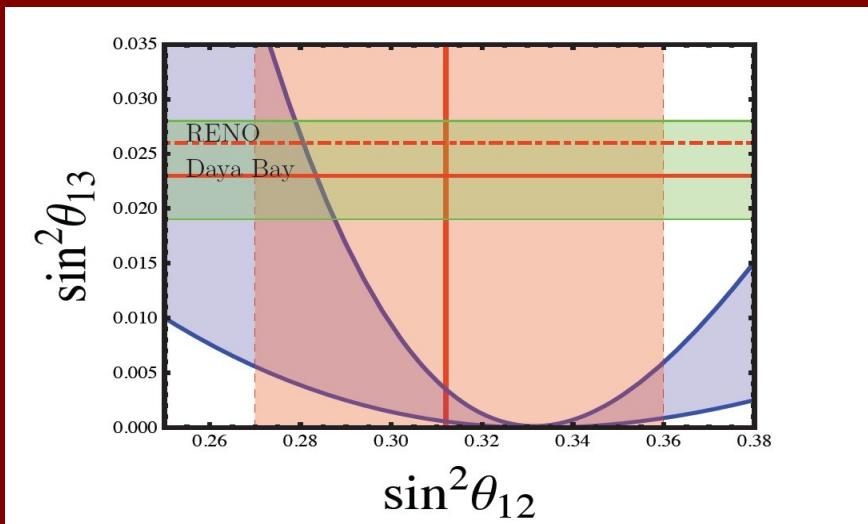


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Boucenna et al  
PhysRevD.86.073008

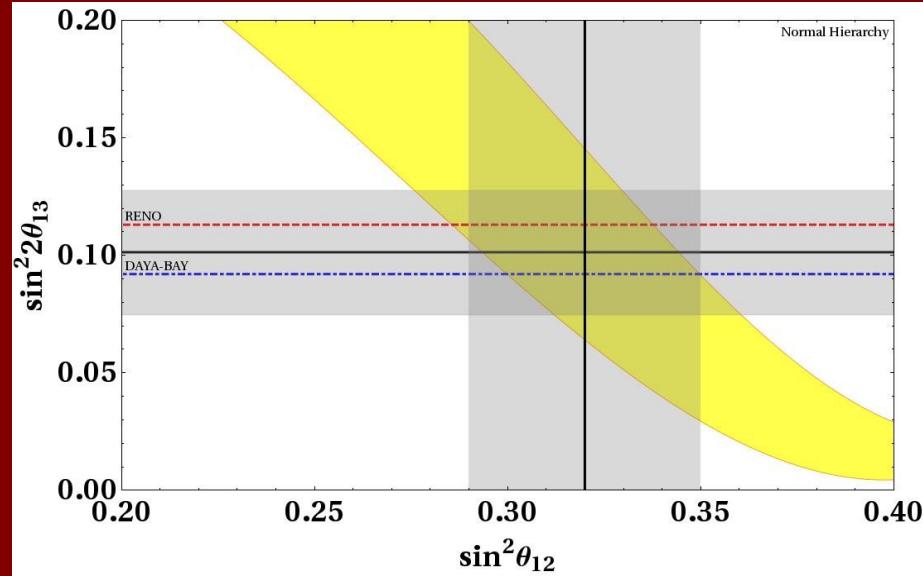


Dorame et al Nucl Phys B861, 259–270



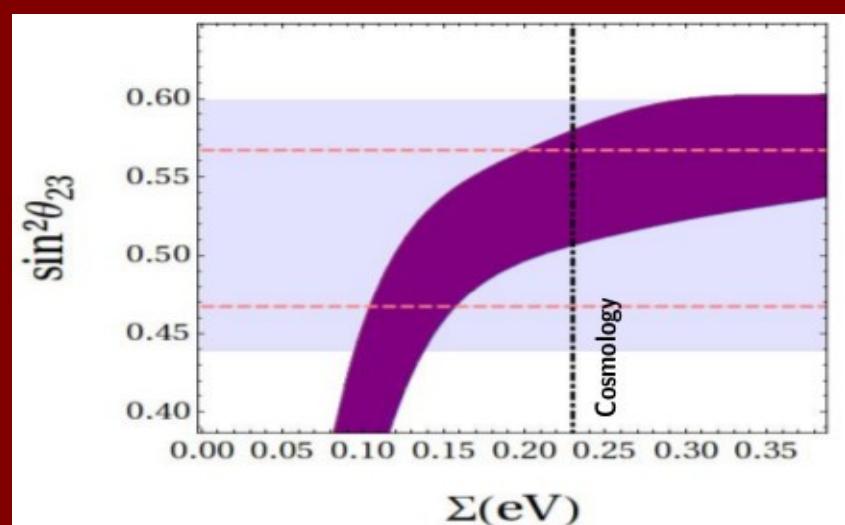
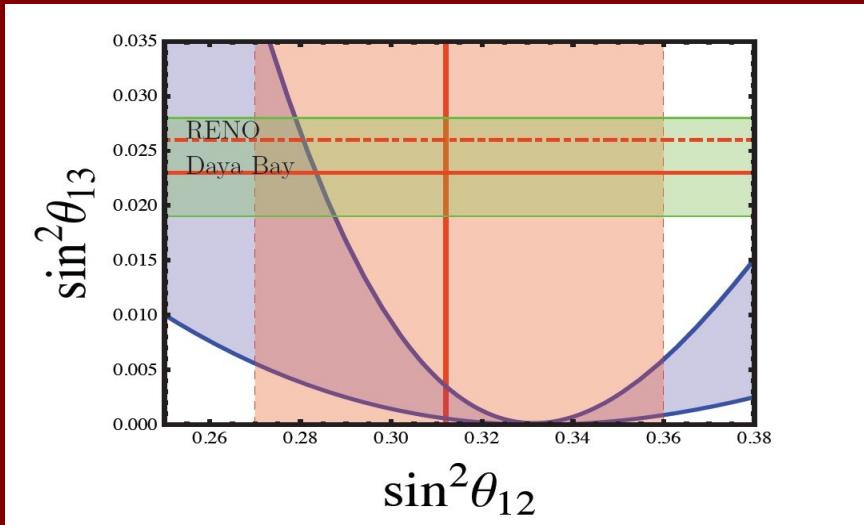
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Boucenna et al  
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Dorame et al Nucl Phys B861, 259–270

**Bonilla et al** Phys.Lett. B742 (2015) 99



# *Bi-large mixing & Cabibbo angle*

Boucenna et al, Phys. Rev. D 86, 051301(R)

# *Bi-large mixing & Cabibbo angle*

Boucenna et al, Phys. Rev. D 86, 051301(R)

*reactor seeds solar & atm*

$$\begin{aligned}\sin \theta_{13} &= \lambda; \\ \sin \theta_{12} &= s \lambda; \\ \sin \theta_{23} &= a \lambda,\end{aligned}$$

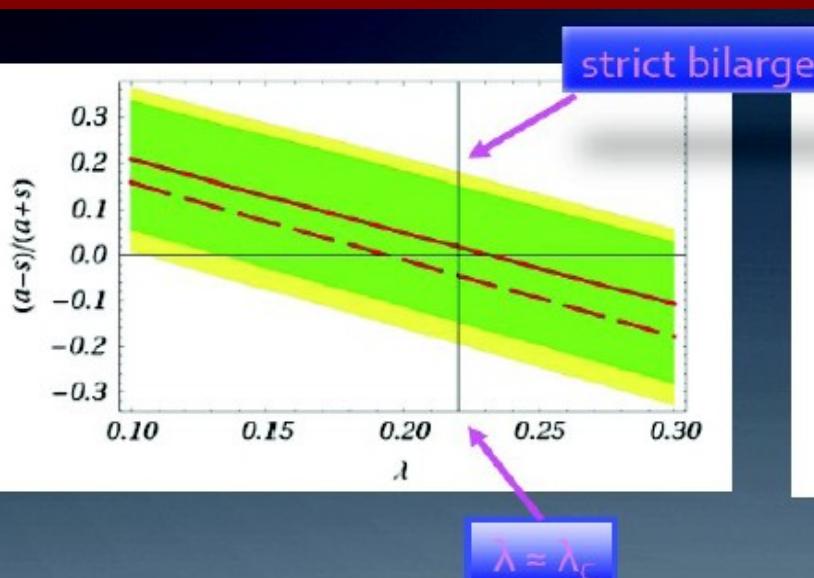
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Ref.	$\lambda$	$s$	$\epsilon$
Forero <i>et al.</i> [14]	$0.23 \pm 0.04$	$2.8^{+0.5}_{-0.4}$	$0.067^{+0.035}_{-0.025}$
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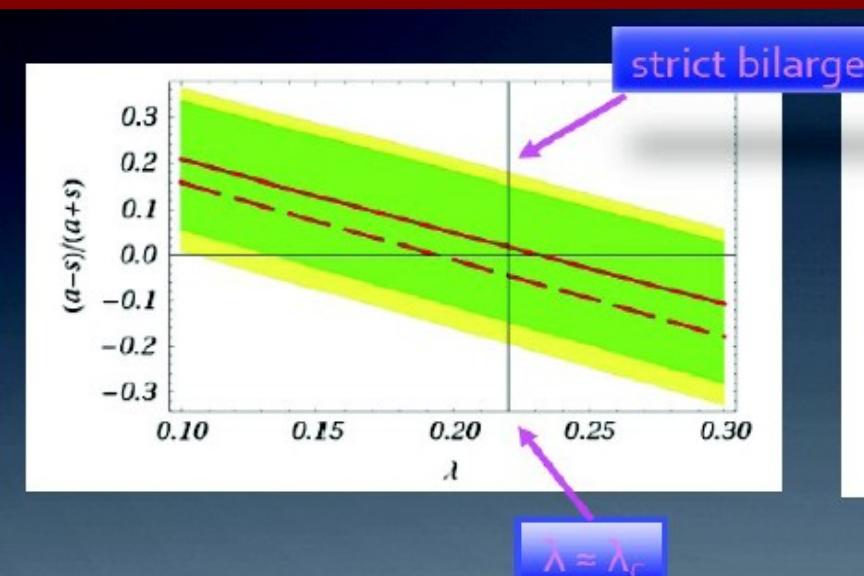
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## Abelian Flavor Models

Ding, et al Phys.Rev. D87 (2013) 053013

Roy, Singh, ..arXiv:1211.7207

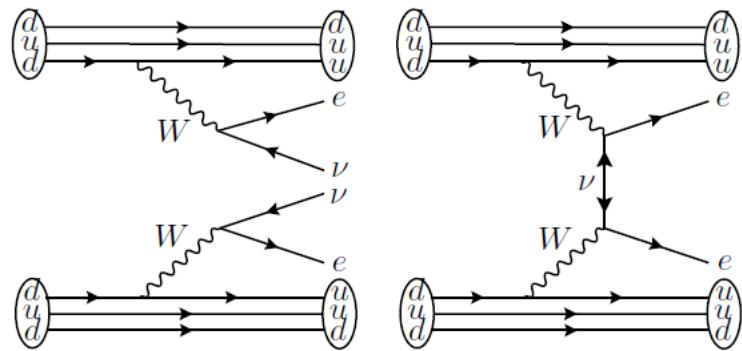
arXiv:1410.3658

The Cabibbo angle as a universal seed for quark and lepton mixings

S. Roy,<sup>1,\*</sup> S. Morisi,<sup>2,†</sup> N. N. Singh,<sup>3,‡</sup> and J. W. F. Valle<sup>4,§</sup>

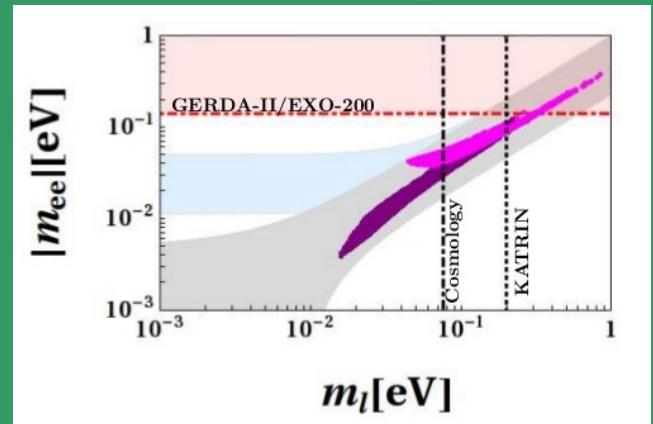
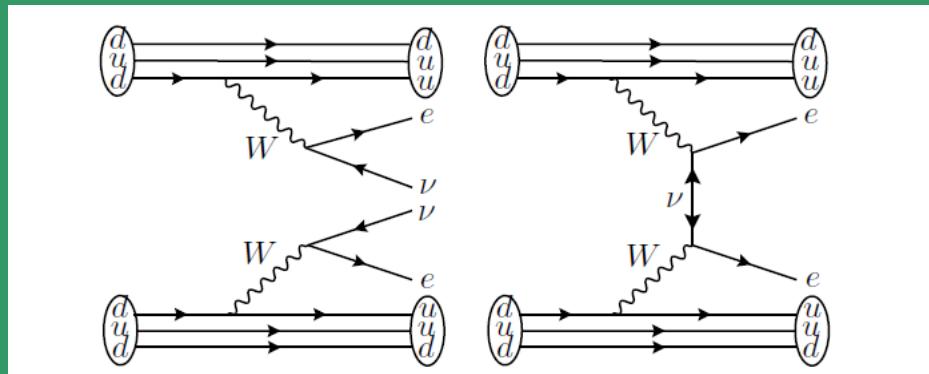
# Neutrinoless Double Beta Decay

A.S. Barabash arXiv:1104.2714



# *Neutrinoless Double Beta Decay and flavor*

A.S. Barabash arXiv:1104.2714

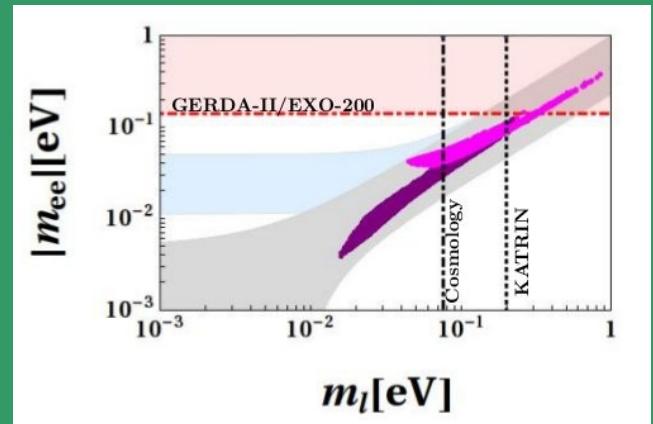
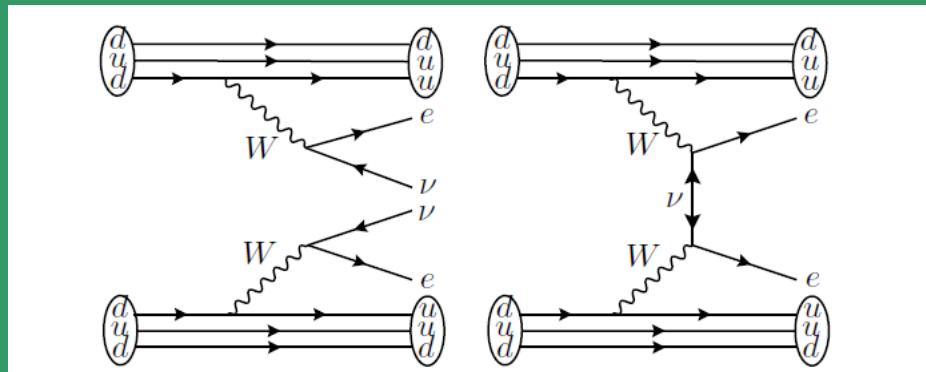


Family symmetry dependent lower bound

Bonilla et al arXiv:1411.4883

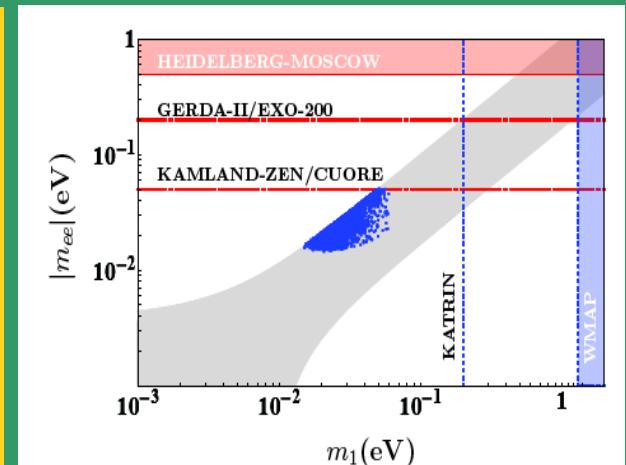
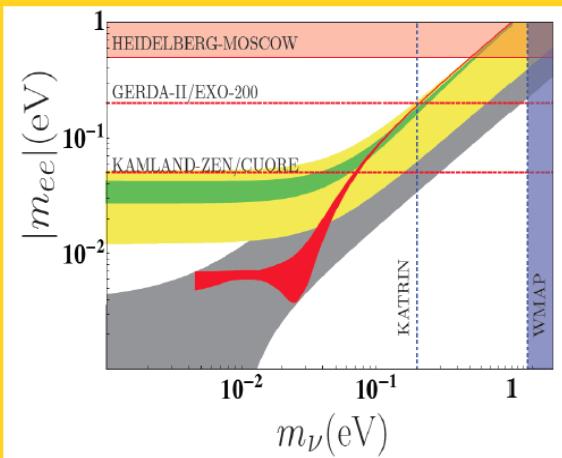
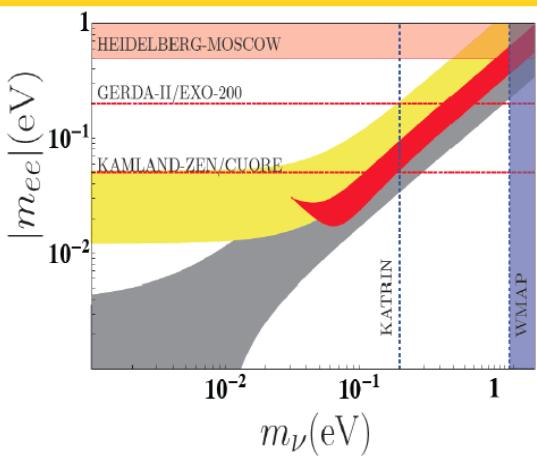
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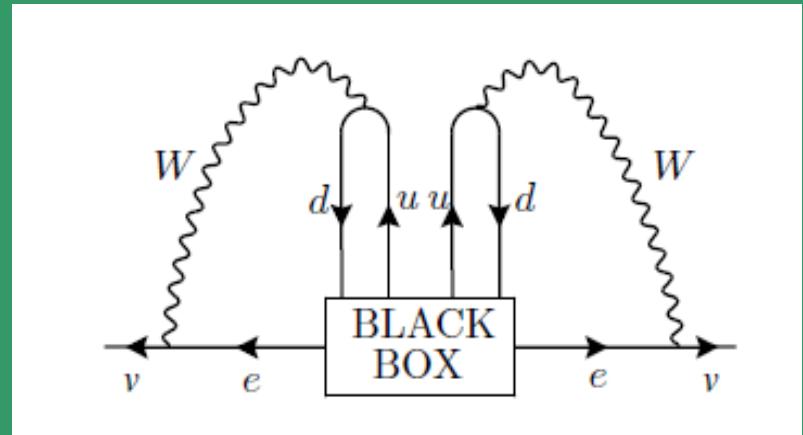
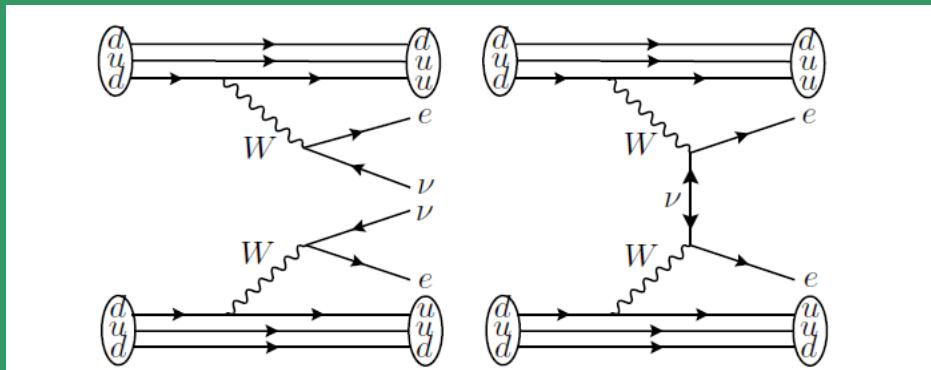
Dorame et al  
NPB861 (2012) 259-270

PhysRevD.86.056001

King et al Phys. Lett. B 724 (2013) 68

# Neutrinoless Double Beta Decay significance

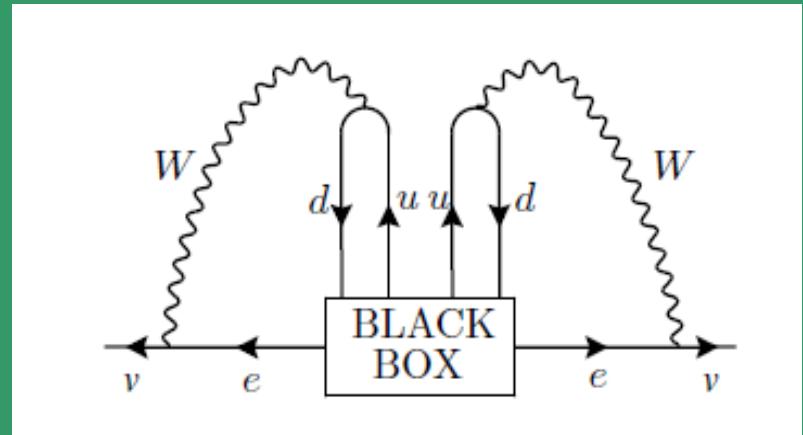
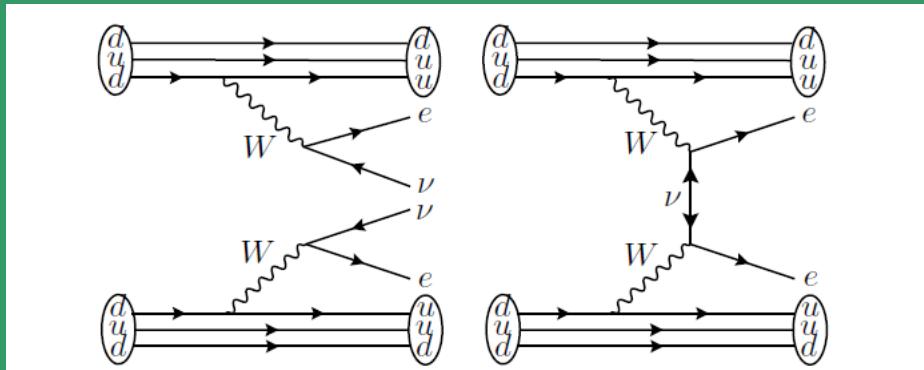
A.S. Barabash arXiv:1104.2714



Schechter, JWPF 82  
Lindner et al JHEP 1106 (2011) 091

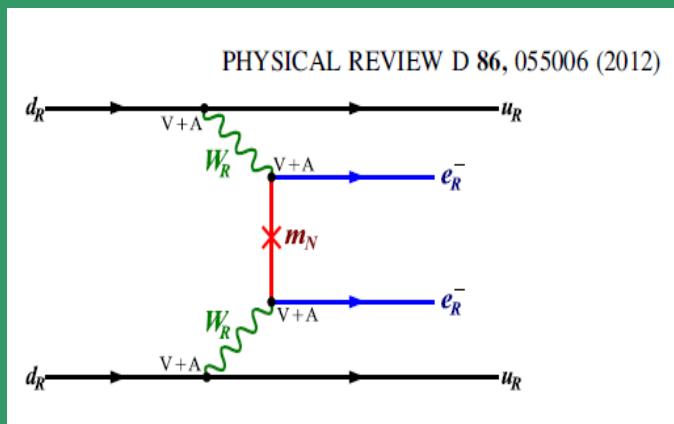
# Neutrinoless Double Beta Decay

A.S. Barabash arXiv:1104.2714



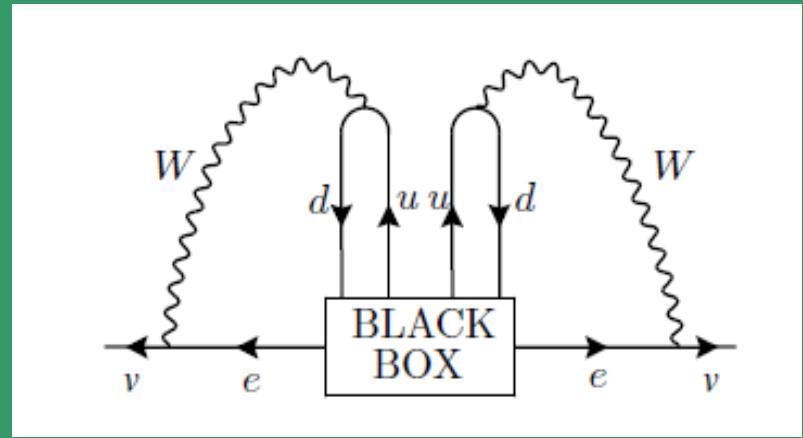
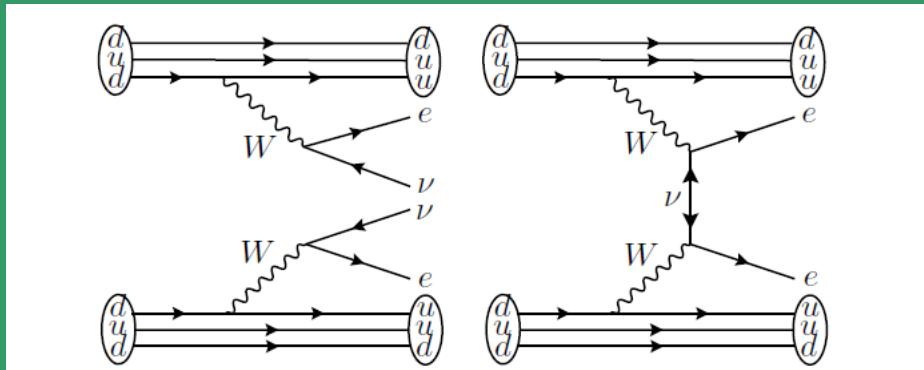
Schechter, JWPF 82  
Lindner et al JHEP 1106 (2011) 091

*Short versus long-range and the LHC*



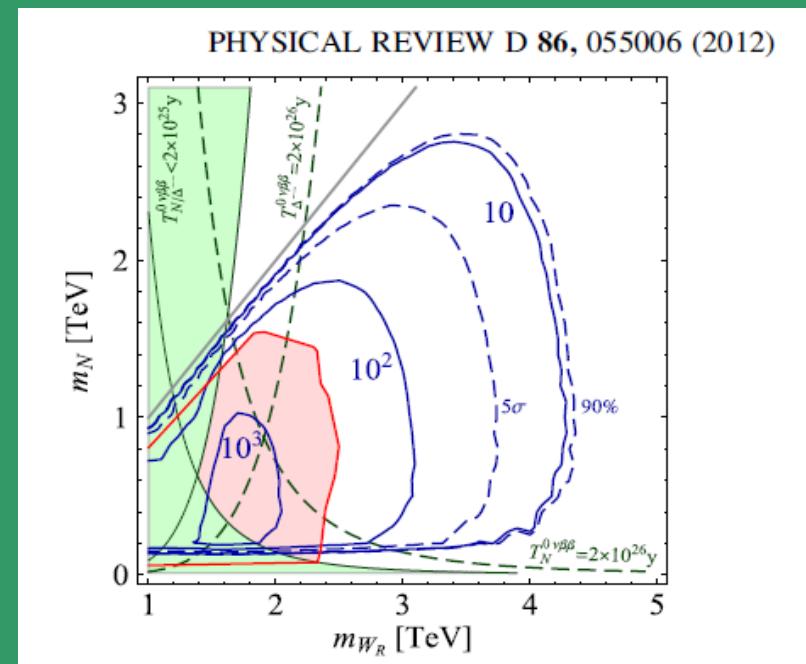
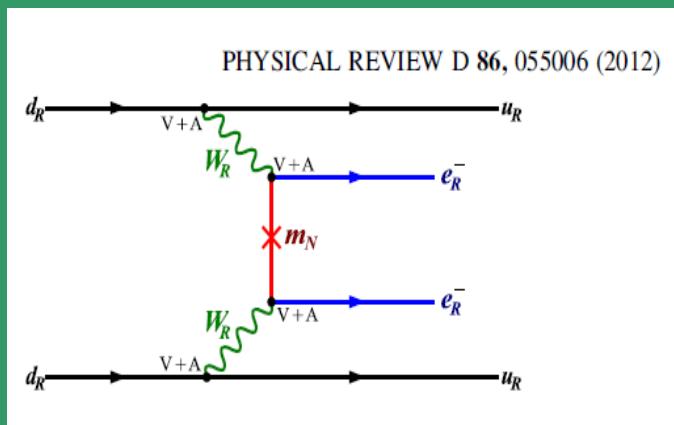
# Neutrinoless Double Beta Decay

A.S. Barabash arXiv:1104.2714

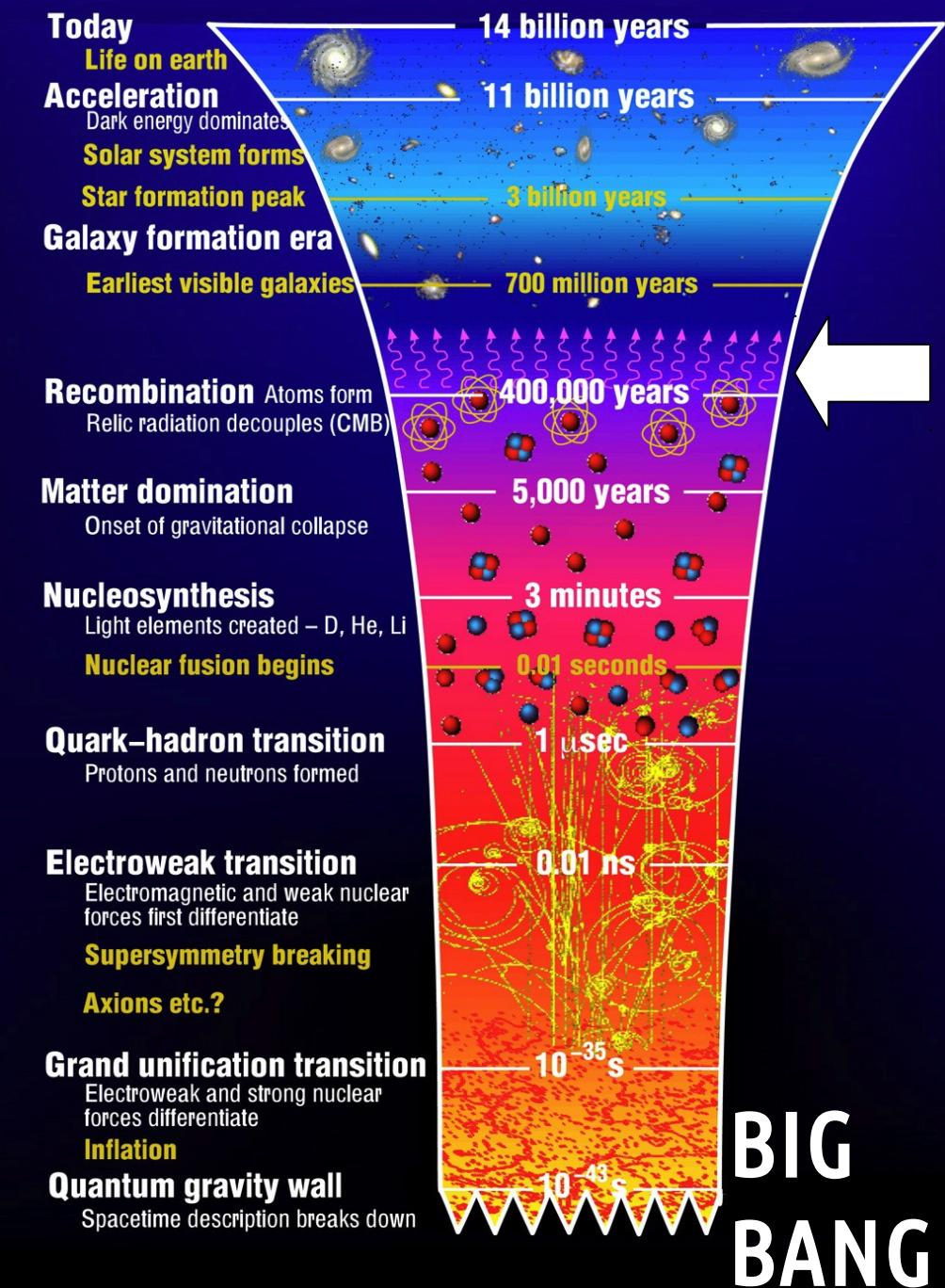


Schechter, JWPF 82  
Lindner et al JHEP 1106 (2011) 091

*Short versus long-range and the LHC*

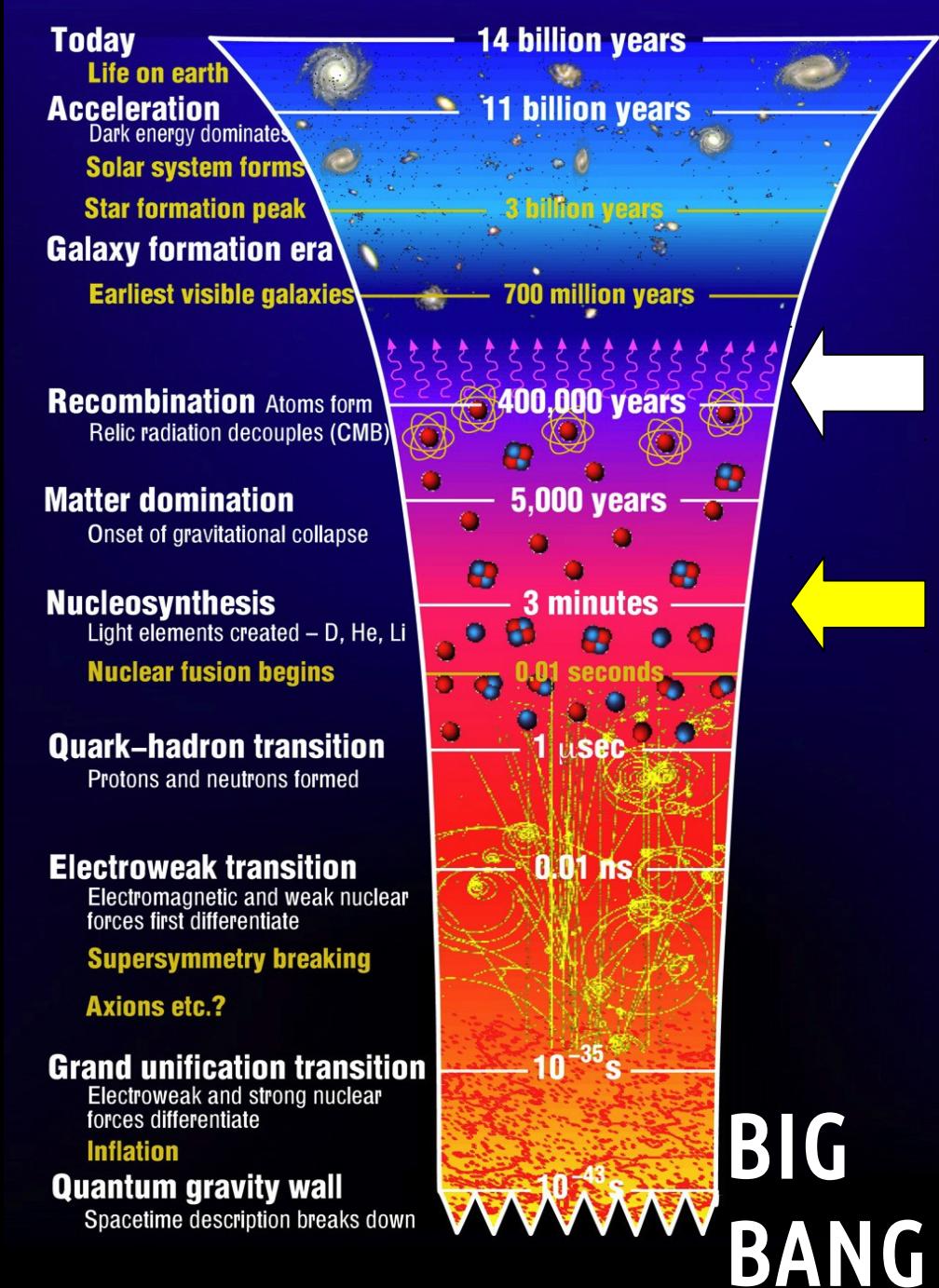


# Neutrinos affect the CMB and large scale structure in the Universe ...



Neutrinos affect the CMB  
and large scale structure  
in the Universe ...

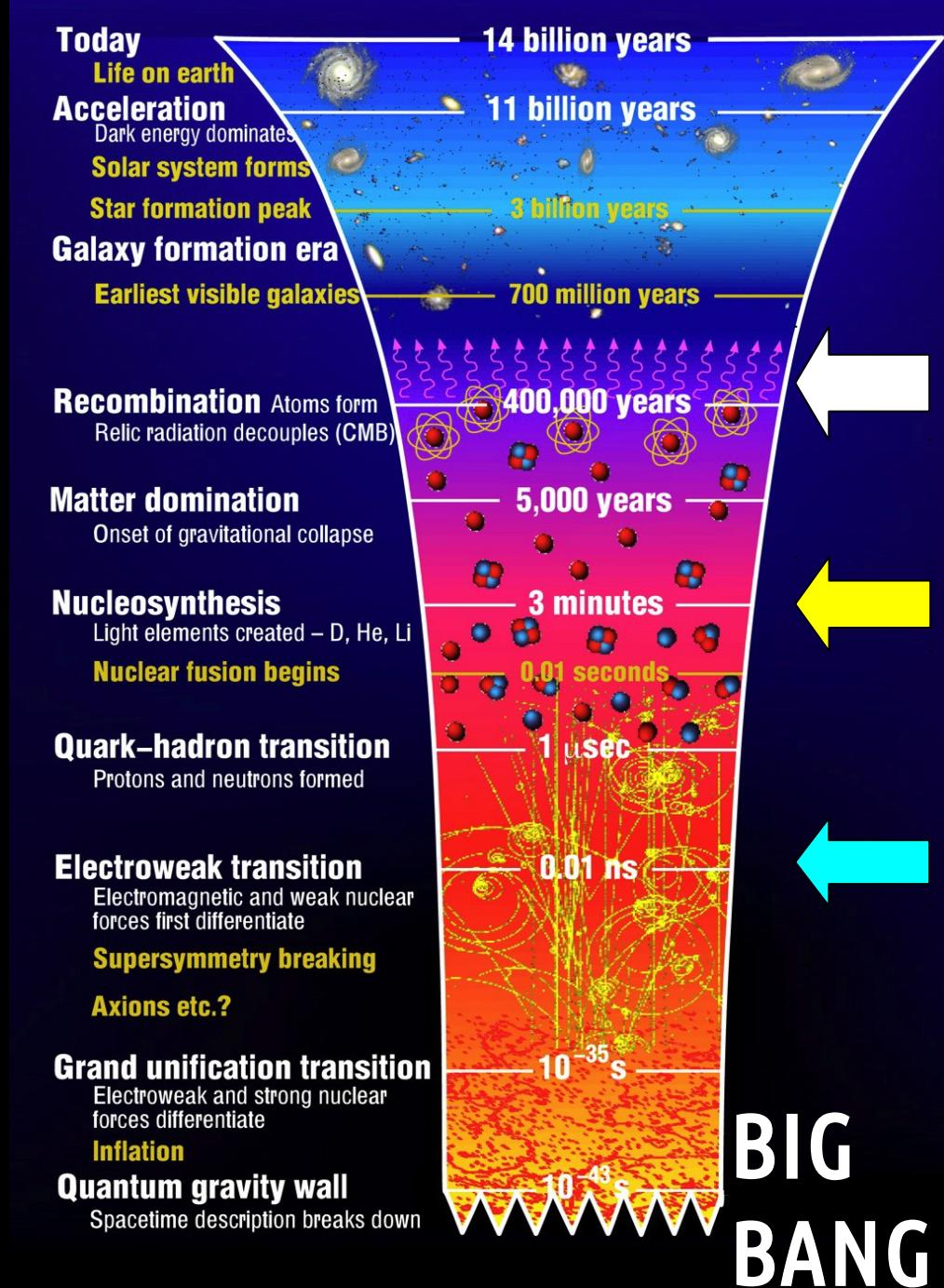
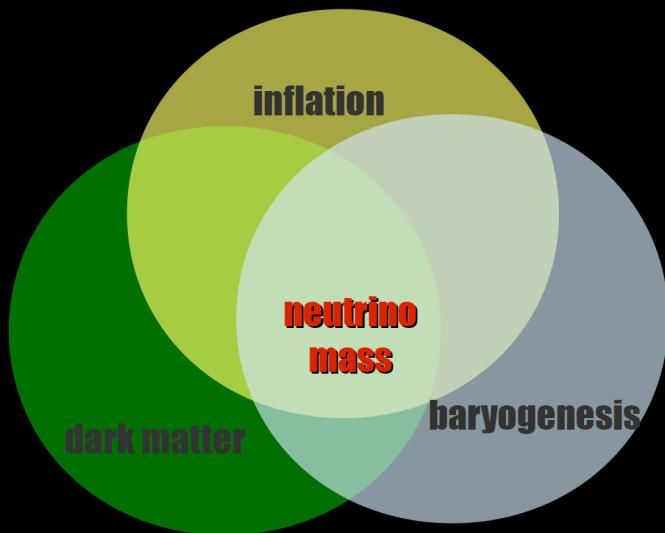
are key in the synthesis of  
light elements



Neutrinos affect the CMB  
and large scale structure  
in the Universe ...

are key in the synthesis of  
light elements

can “probe” the Universe  
earlier than photons ...



# SEESAW INFLATION & MAJORON DARK MATTER

$$\sigma = \frac{1}{\sqrt{2}}(\langle \sigma \rangle + \rho + iJ)$$

NEUTRINO MASSES

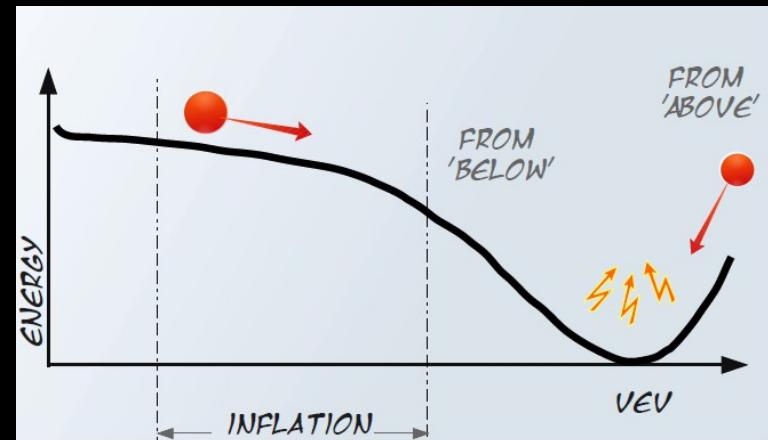
Inflaton

DARK MATTER

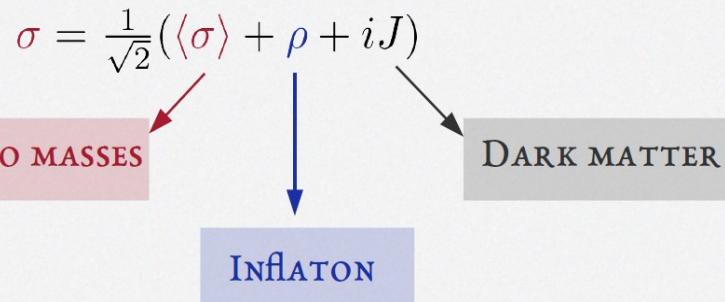
Boucenna et al arXiv:1405.2332

PRD90 (2014) 055023

type-I seesaw



# SEESAW INFLATION & MAJORON DARK MATTER

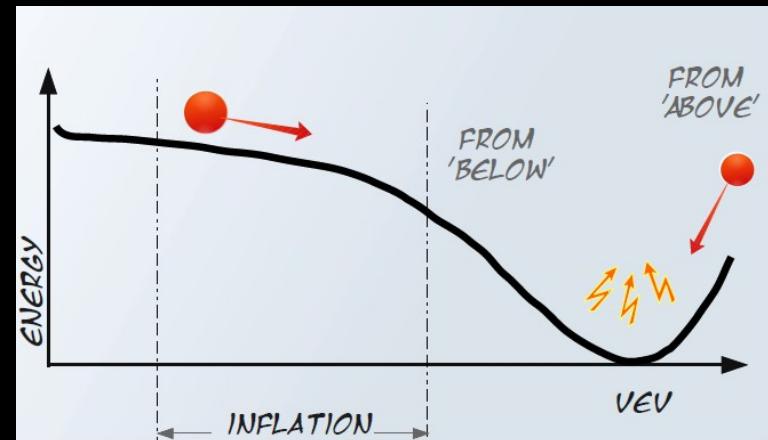
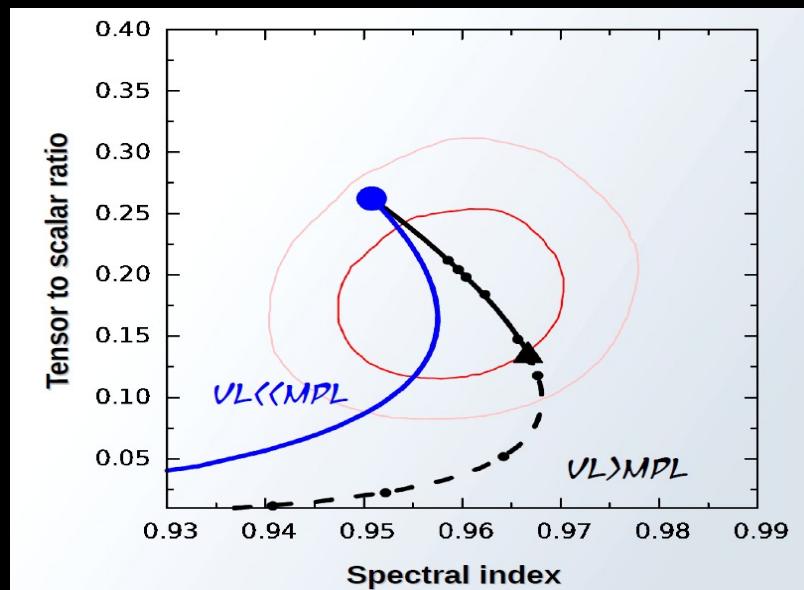


Boucenna et al arXiv:1405.2332

PRD90 (2014) 055023

type-I seesaw

*Quartic versus Higgs Inflation*



but <http://arxiv.org/pdf/1502.00612v1>

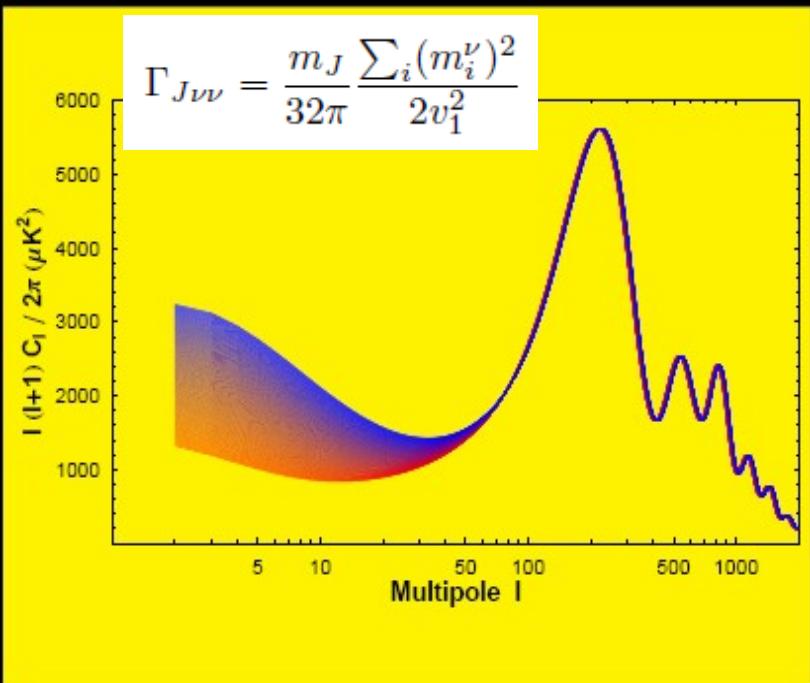
$$\Gamma_{J\nu\nu} = \frac{m_J}{32\pi} \frac{\sum_i (m_i^\nu)^2}{2v_1^2}$$

# DARK MATTER MAJORONS

## Consistency with CMB

Berezinsky, Valle PLB318 (1993) 360

Lattanzi & Valle, PRL99 (2007) 121301



Esteves et al, PRD 82, 073008 (2010)

Bazzocchi & al JCAP 0808 (2008) 013

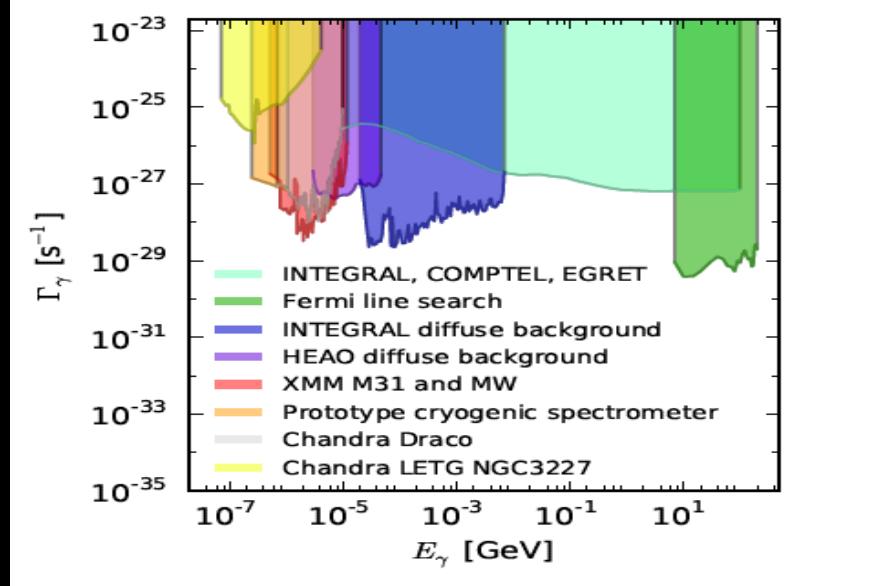
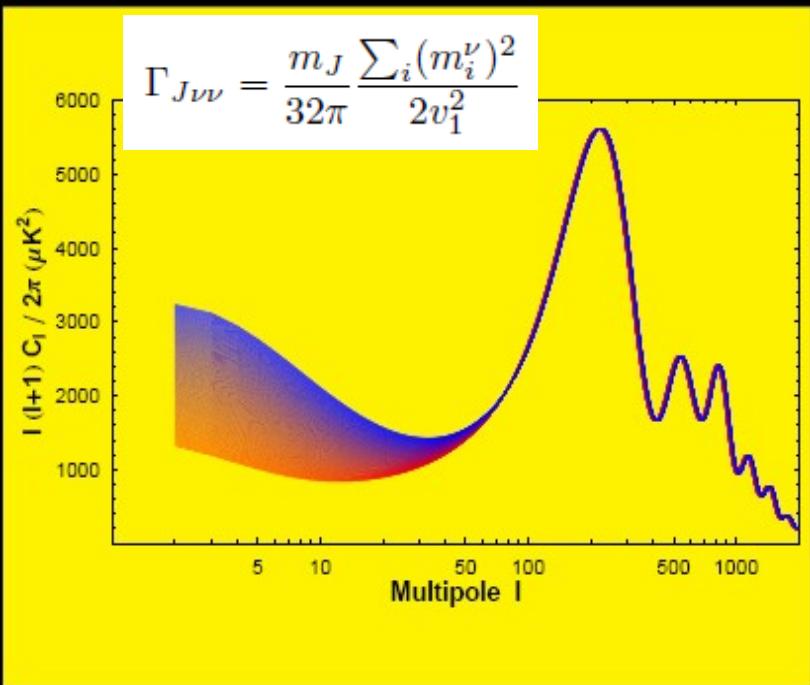
# DARK MATTER MAJORONS

Consistency with CMB

$J \rightarrow \gamma\gamma$

Berezinsky, Valle PLB318 (1993) 360

Lattanzi & Valle, PRL99 (2007) 121301



Lattanzi et al PRD88 (2013) 063528

Esteves et al, PRD 82, 073008 (2010)

Bazzocchi & al JCAP 0808 (2008) 013

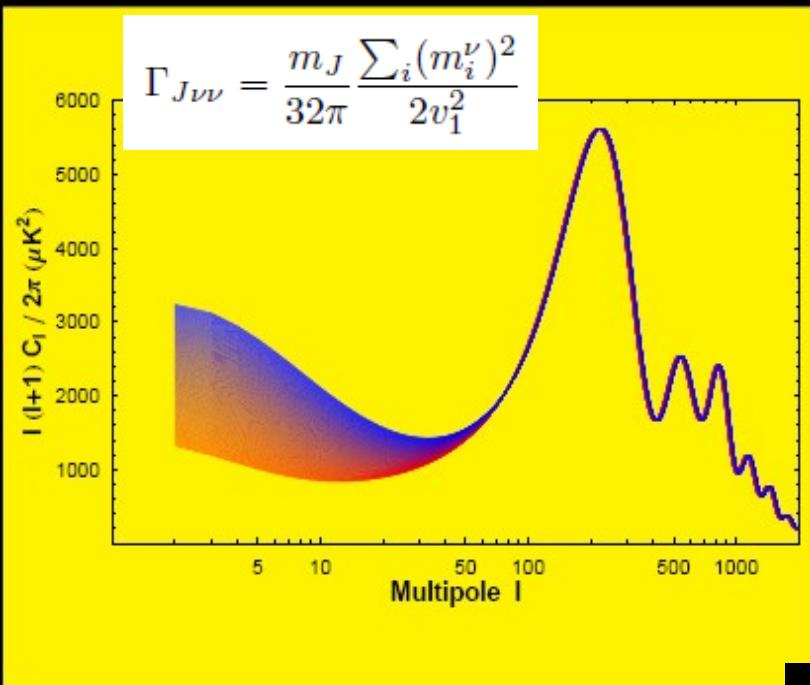
# DARK MATTER MAJORONS

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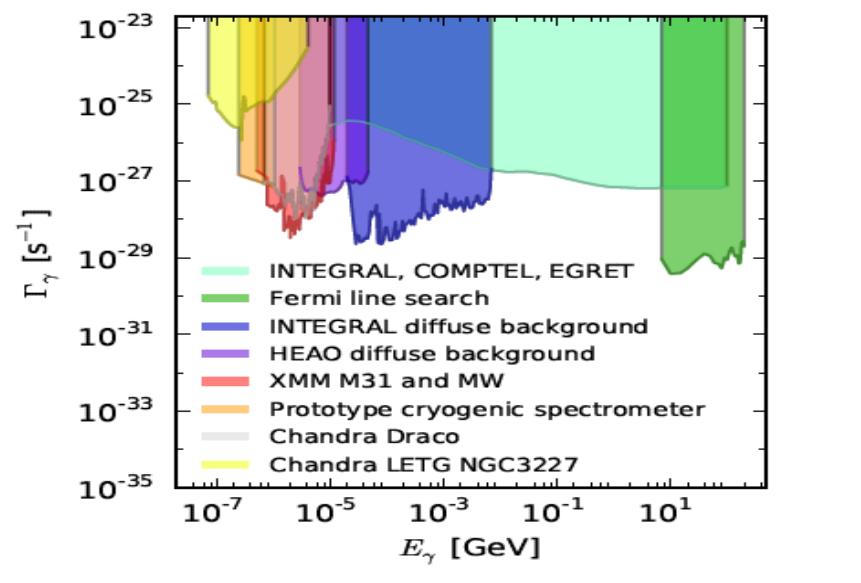
Berezinsky, Valle PLB318 (1993) 360

Lattanzi & Valle, PRL99 (2007) 121301

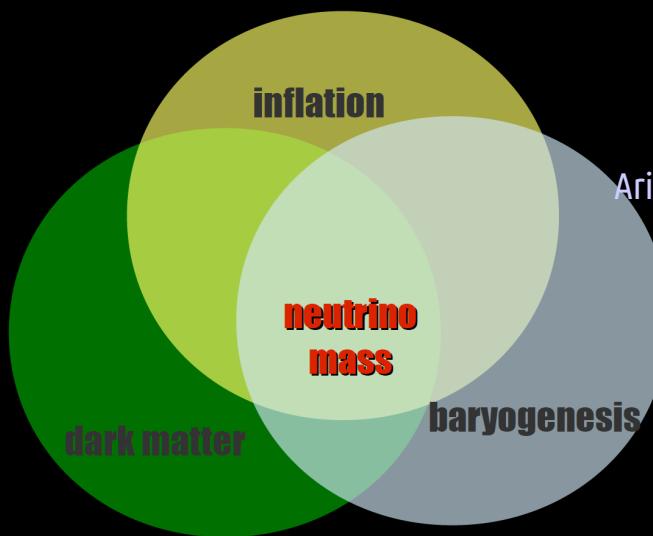


Esteves et al, PRD 82, 073008 (2010)

Bazzocchi & al JCAP 0808 (2008) 013



Lattanzi et al PRD88 (2013) 063528



Aristizabal et al arXiv:1405.4706

*Leptogenesis in  
dynamical  
seesaw*    JCAP

# DARK MATTER STABILITY FROM FLAVOUR SYMMETRY

# DARK MATTER STABILITY FROM FLAVOUR SYMMETRY

- *accidental?* Lavoura, Morisi, JV JHEP 1302(2013) 118
- *unbroken subgroup* Hirsch, Morisi, Peinado, Valle  
PRD82 116003 (2010)

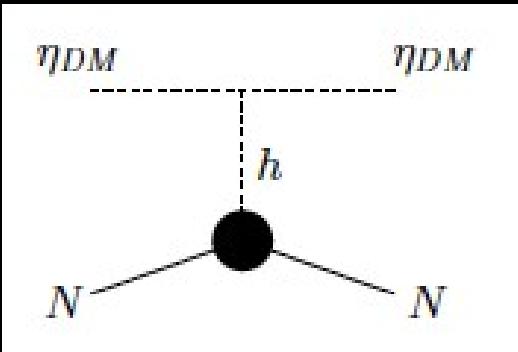
# DARK MATTER FROM FLAVOUR SYMMETRY

- *accidental?*
- *unbroken subgroup*



Z2 PARITY

HIGGS PORTAL  
DIRECT DETECTION

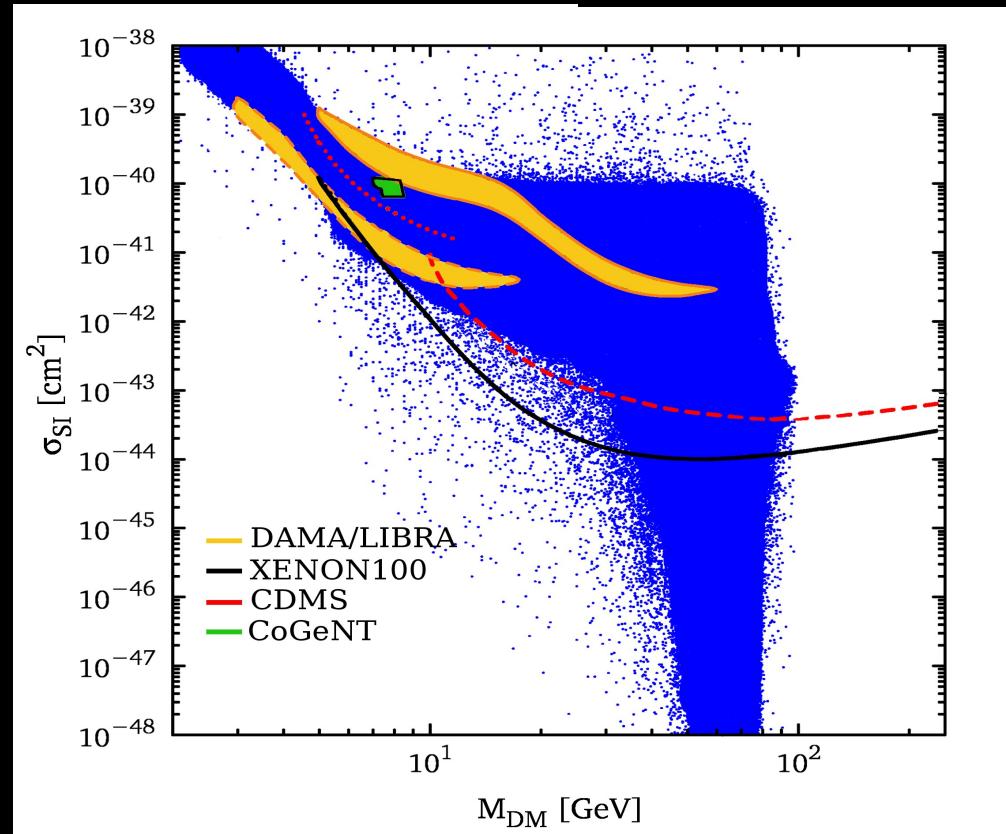


Lavoura, Morisi, JV JHEP 1302(2013) 118

Hirsch, Morisi, Peinado, Valle  
PRD82 116003 (2010)

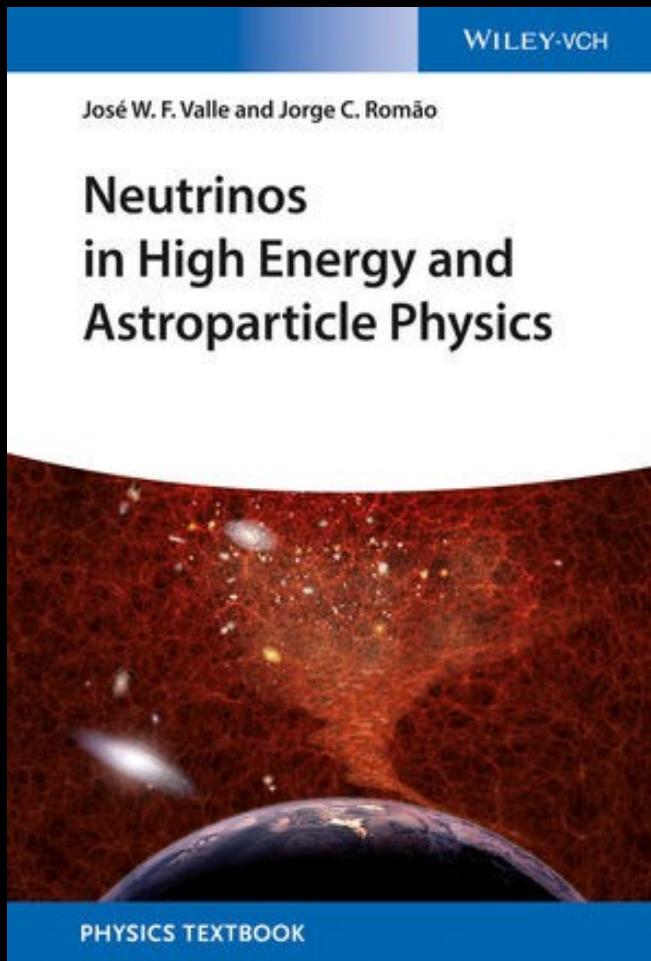
Boucenna et al

JHEP 1105 037 (2011)



*Thank you !!*

more at



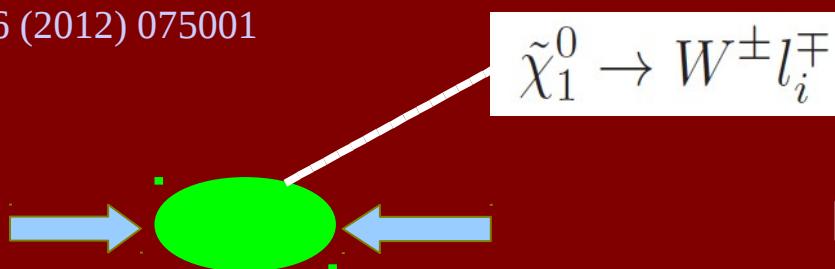
ISBN: 978-3-527-41197-9  
456 pages  
February 2015

*Now the backup slides*

# LIGHTEST NEUTRALINO DECAYS: PROBING NEUTRINOS @ LHC

De Campos et al

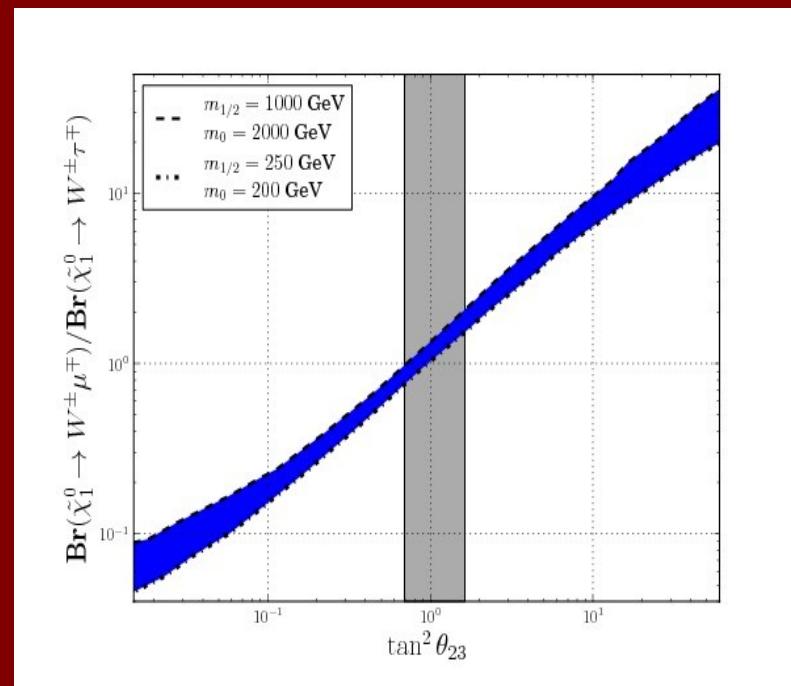
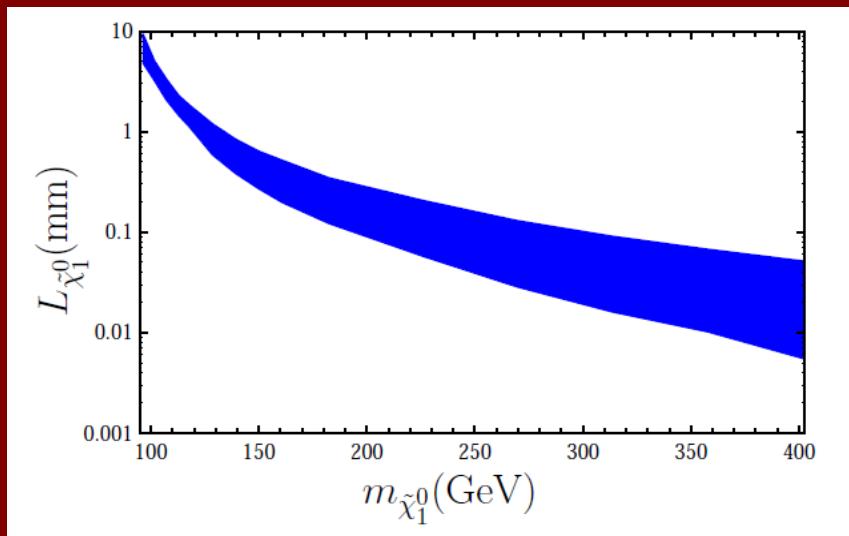
Phys.Rev. D86 (2012) 075001



$$\tilde{\chi}_1^0 \rightarrow Z^0 \nu_i$$

Lightest neutralino decay correlates with atm angle

Lightest neutralino decay length



# *decaying Gravitino dark matter*

decays suppressed by Planck mass & smallness of m- $\nu$

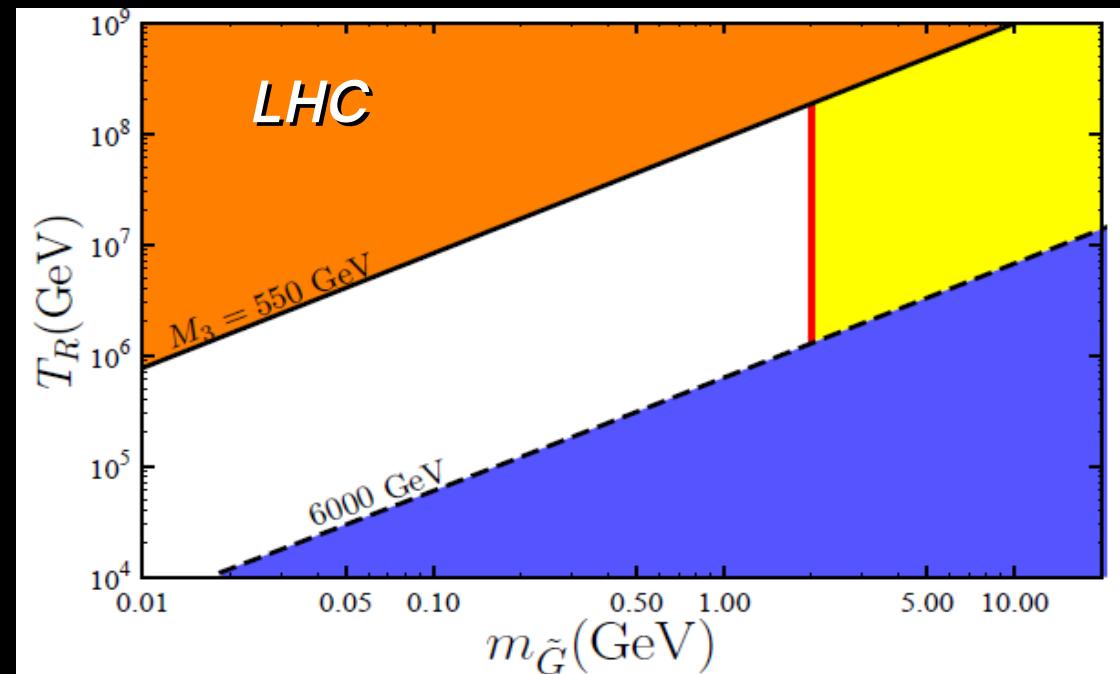
$$\Gamma = \Gamma(\tilde{G} \rightarrow \sum_i \nu_i \gamma) \simeq \frac{1}{32\pi} |U_{\tilde{\gamma}\nu}|^2 \frac{m_{\tilde{G}}^3}{M_P^2}$$

chosen to fit neutrino osc. data

Restrepo et al  
PRD85 (2012) 023523

relic abundance  
+ LHC searches

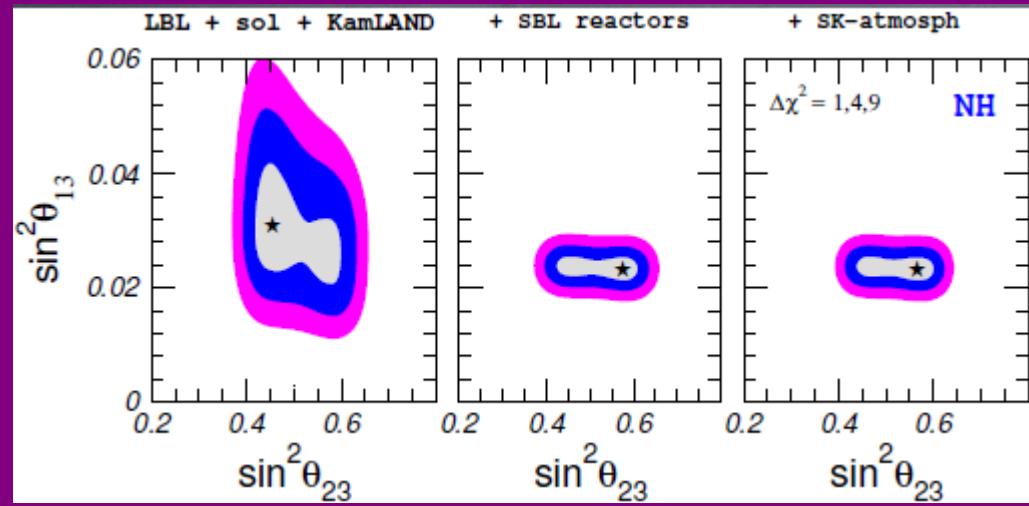
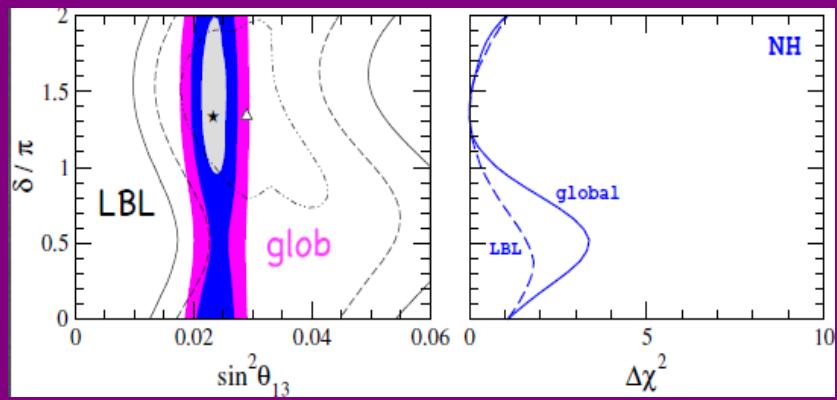
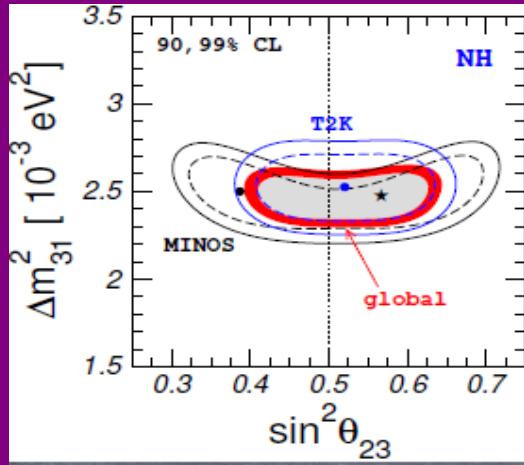
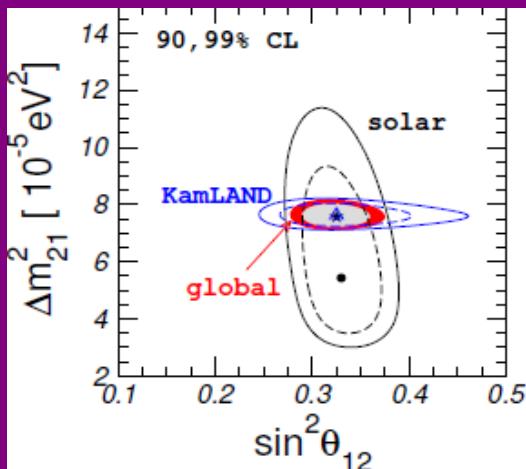
excluded by gamma  
line searches @  
Egret & Fermi-LAT



# Oscillations after nu2014

Forero, Tortola, JWFV arXiv:1405.7540

PHYSICAL REVIEW D 90, 093006 (2014)



Double Chooz: 467.9 days [arXiv:1406.7763]

RENO: 800 days [talk by Seon-Hee Seo@ICHEP2014]

Daya Bay: 621 days of data (6AD + 8AD) [Talk by Chao Zhang@ICHEP2014]

# WIMP DARK MATTER

If neutrinos get mass a  
la Inverse seesaw susy  
Spectrum can change so ...

LSP is SNEUTRINO-like

*instead of neutralino ..*

Arina et al PRL101 (2008) 161802

Bazzocchi, Cerdeno, Munoz, J.V., PRD81 (2010) 051701

De Romeri, Hirsch, JHEP 1212 (2012) 106

