

# Neutrino Landscape 2016

José W F Valle



<https://www.facebook.com/ific.ahep/>

Humboldt Kolleg "From the Vacuum to the Universe", Kitzbühel Austria, June-2016

# Why neutrinos

*Can not do without neutrinos*

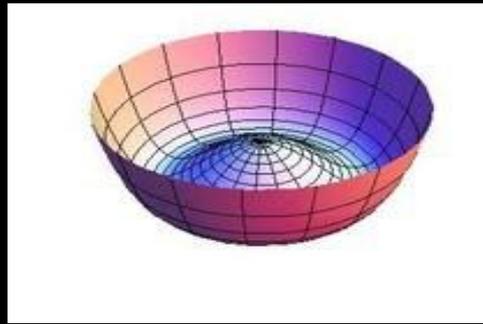
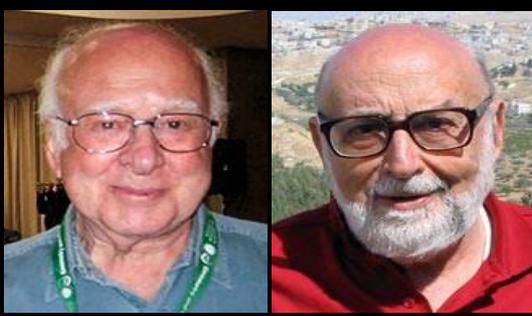
*Basic cosmological and astro probe*

*key building block of the Standard Model*

# Standard model

Three Generations of Matter (Fermions) spin  $\frac{1}{2}$

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon
	Left Right	Left Right	Left Right	
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
Quarks	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon
	Left Right	Left Right	Left Right	
	0 eV	0 eV	0 eV	91.2 GeV
	0	0	0	0
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>Z<sup>0</sup></b> weak force
	Left Right	Left Right	Left Right	
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
Leptons	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>W<sup>±</sup></b> weak force
	Left Right	Left Right	Left Right	
				Bosons (Forces) spin 1

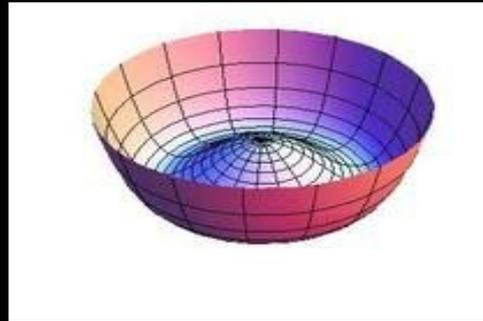
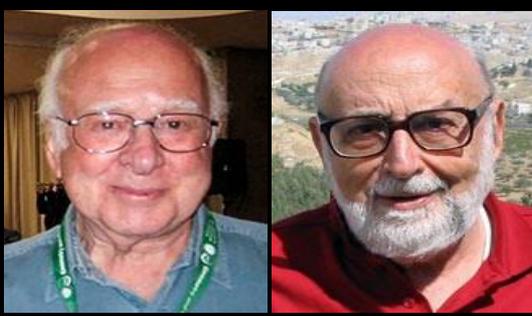


# Standard model

125 GeV
<b>H</b>
Higgs boson
spin 0

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	Left Right	Left Right	Left Right	0
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	0
Quarks	Left Right	Left Right	Left Right	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	91.2 GeV
	0 eV	0 eV	0 eV	0
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Leptons	Left Right	Left Right	Left Right	0
	-1	-1	-1	±
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
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				spin 1



# Standard model

125 GeV  
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Last brick? ...

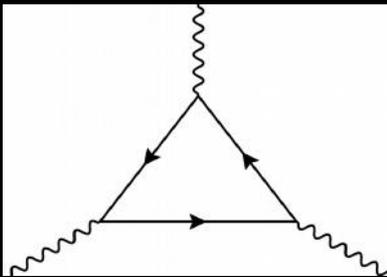
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Quarks	4.8 MeV -1/3 <b>d</b> Left down Right	104 MeV -1/3 <b>s</b> Left strange Right	4.2 GeV -1/3 <b>b</b> Left bottom Right	0 0 <b>γ</b> photon
Leptons	0 eV 0 <b>ν<sub>e</sub></b> electron neutrino	0 eV 0 <b>ν<sub>μ</sub></b> muon neutrino	0 eV 0 <b>ν<sub>τ</sub></b> tau neutrino	91.2 GeV 0 <b>Z<sup>0</sup></b> weak force
	0.511 MeV -1 <b>e</b> Left electron Right	105.7 MeV -1 <b>μ</b> Left muon Right	1.777 GeV -1 <b>τ</b> Left tau Right	80.4 GeV ±1 <b>W<sup>±</sup></b> weak force

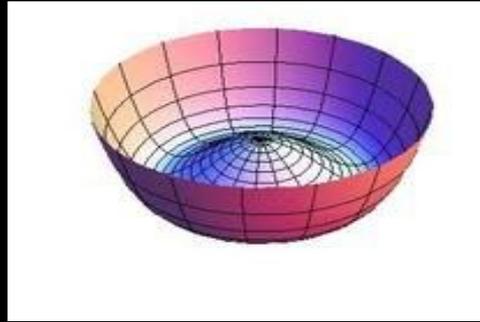
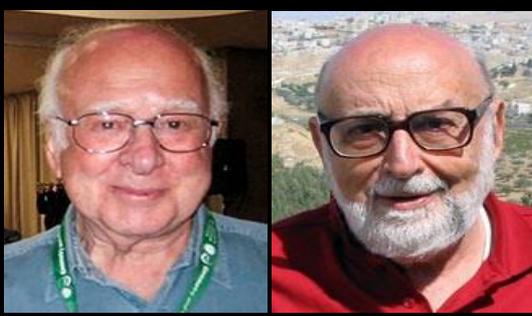
Bosons (Forces) spin 1

$$-\frac{1}{2} \quad -\frac{1}{2} \quad \frac{1}{6} \quad \frac{1}{6} \quad -1 \quad \frac{2}{3} \quad -\frac{1}{3}$$

anomalies



Charge quantization



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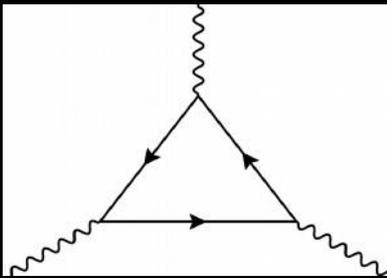
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Leptons	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	<b>e</b> Left electron Right	<b>μ</b> Left muon Right	<b>τ</b> Left tau Right	<b>W<sup>±</sup></b> weak force
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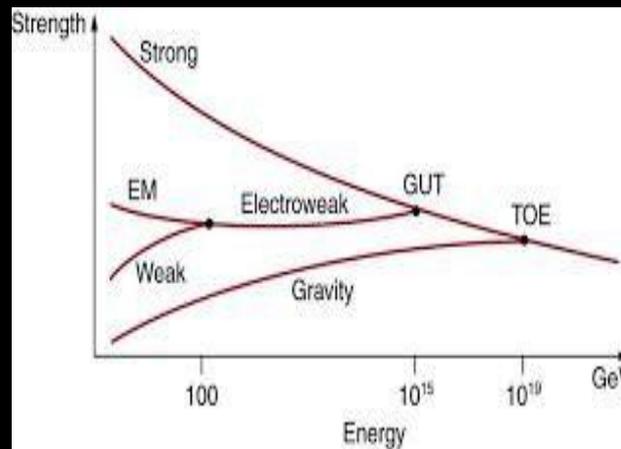
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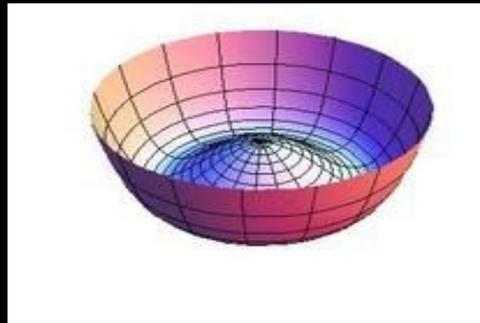
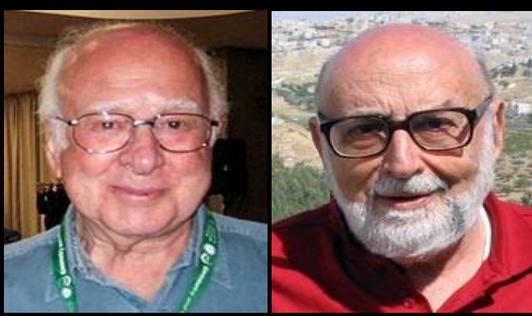
anomalies

coupling unification



Charge quantization





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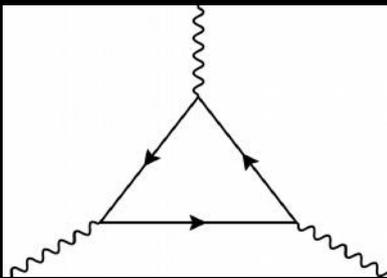
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	0 eV	0 eV	0 eV	91.2 GeV
	<b>ν<sub>e</sub></b> Left electron neutrino Right	<b>ν<sub>μ</sub></b> Left muon neutrino Right	<b>ν<sub>τ</sub></b> Left tau neutrino Right	0
Leptons	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	<b>e</b> Left electron Right	<b>μ</b> Left muon Right	<b>τ</b> Left tau Right	+1
				<b>Z</b> weak force
				<b>W<sup>±</sup></b> weak force

Bosons (Forces) spin 1

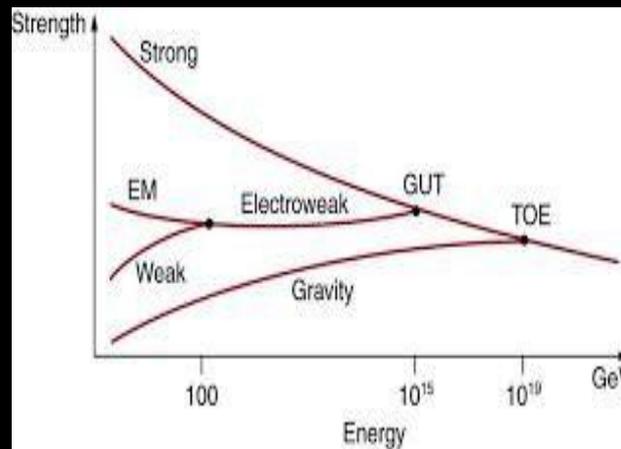
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anomalies

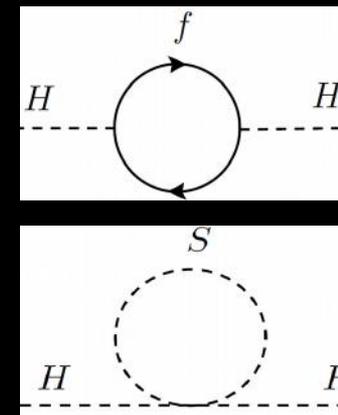


Charge quantization

coupling unification



Consistency of SSB

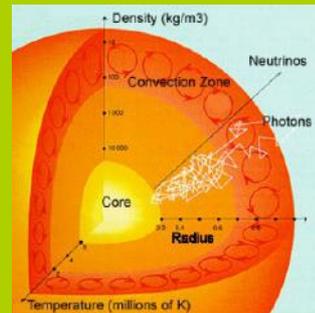


Gravity ...

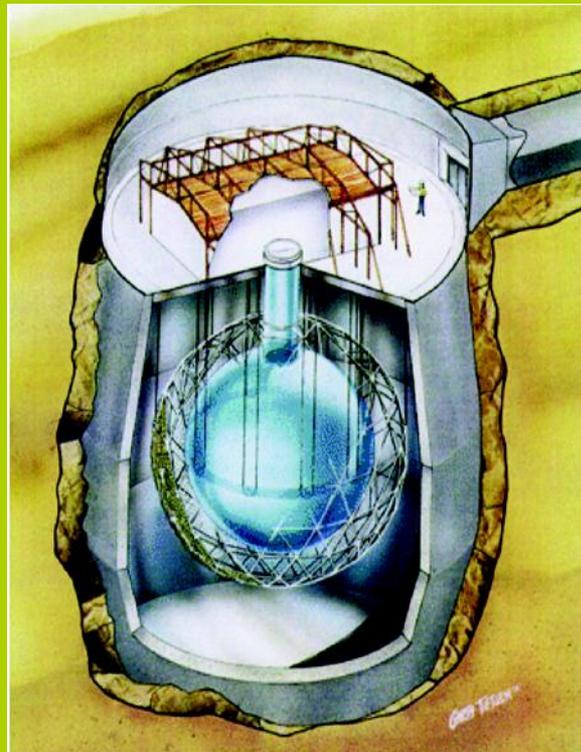
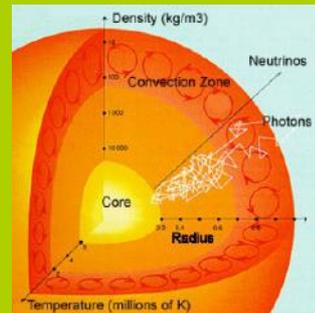
Why 3 families ...

Neutrino mass

# Neutrino oscillations

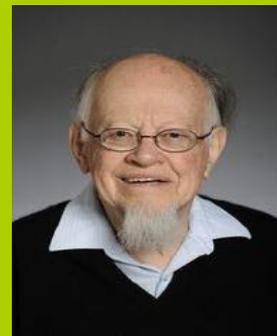
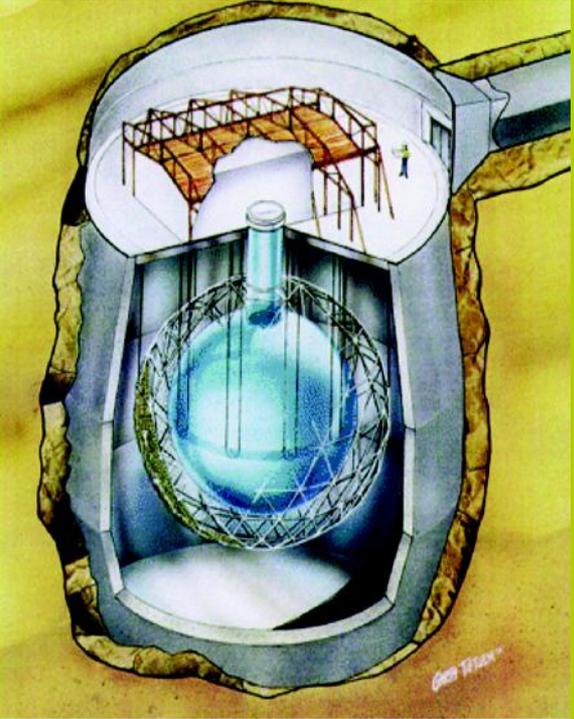
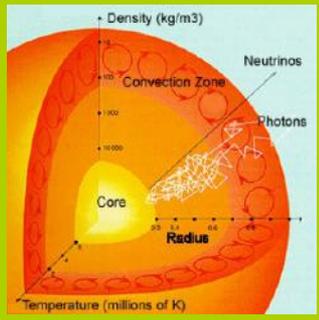
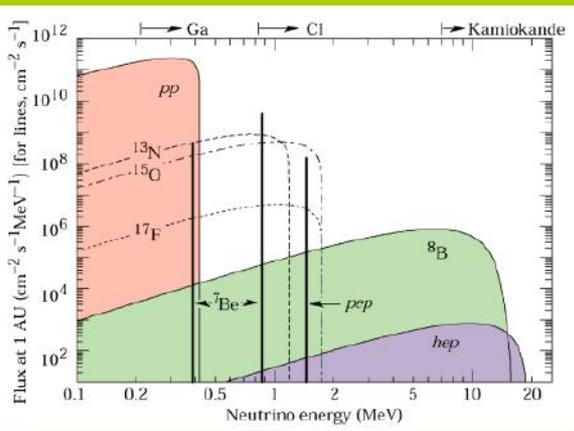


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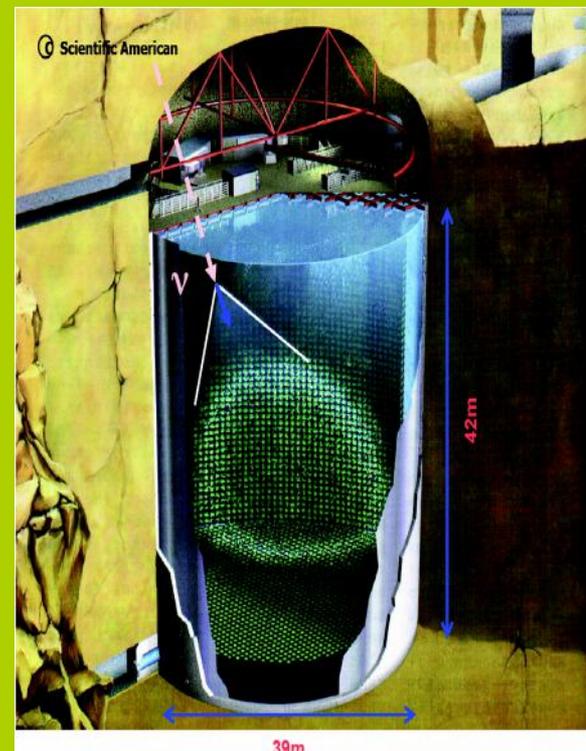
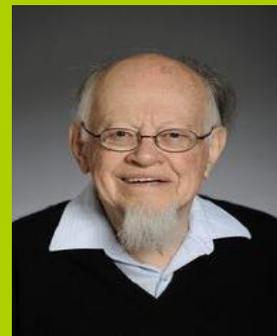
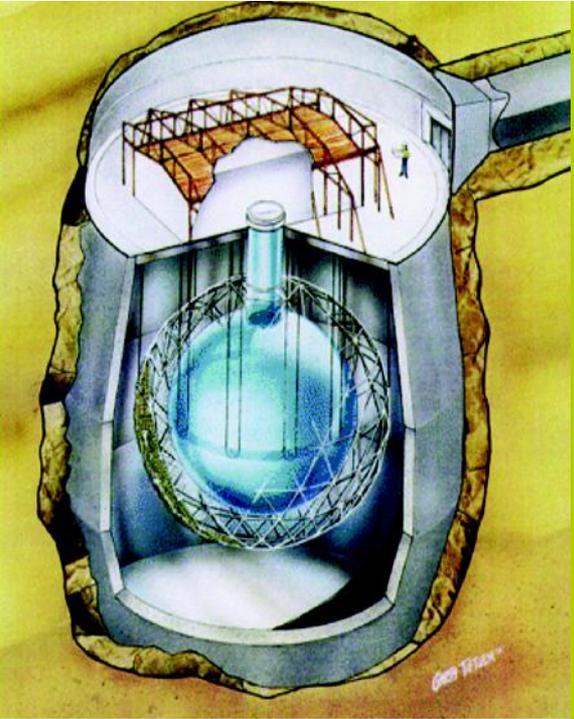
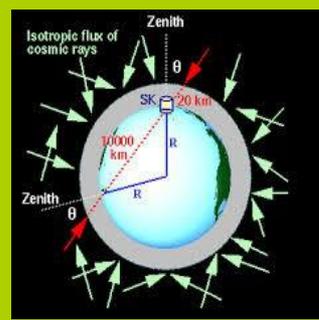
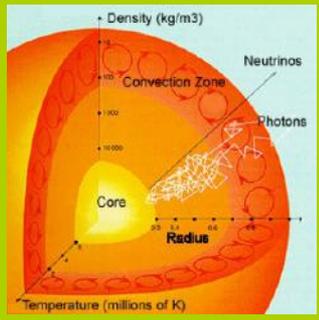
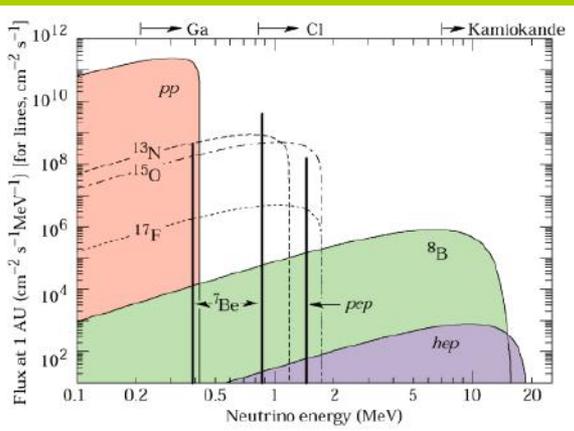


Valle

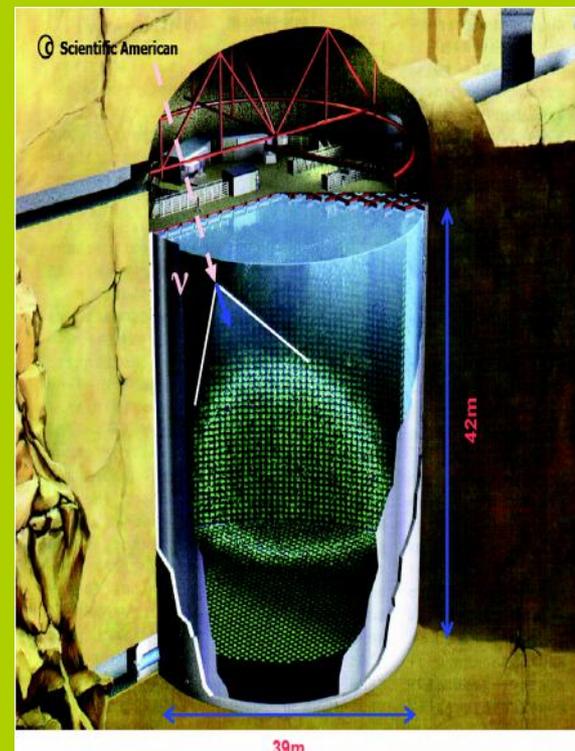
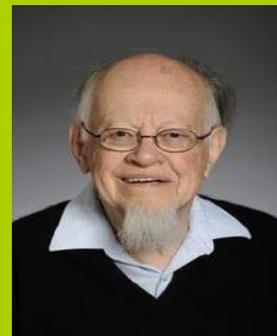
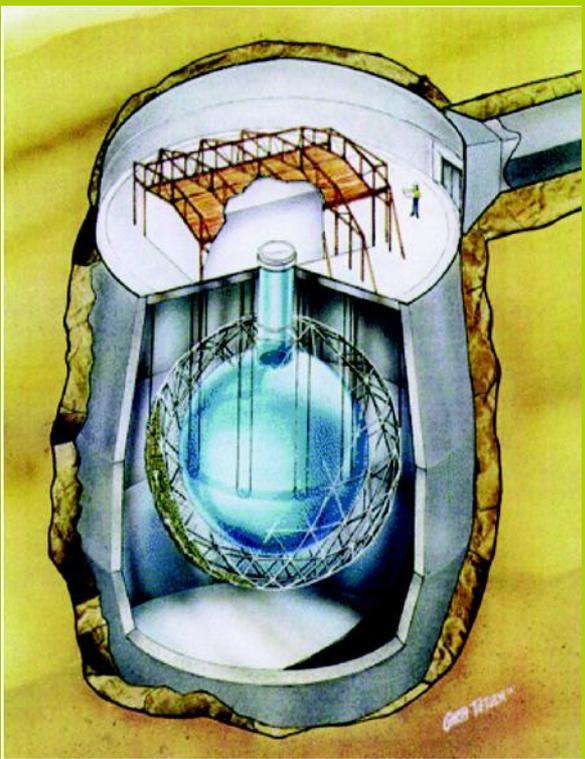
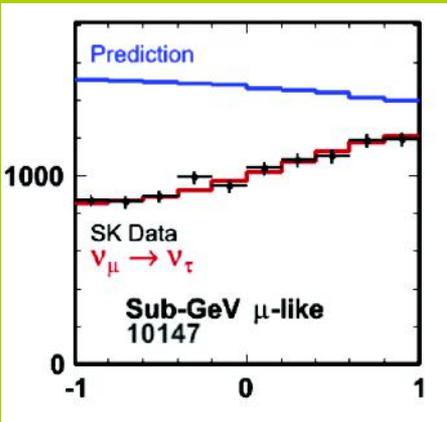
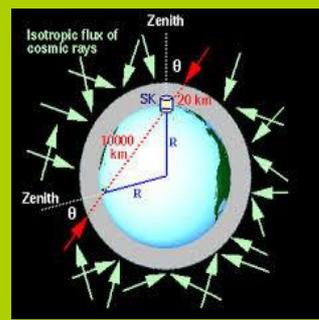
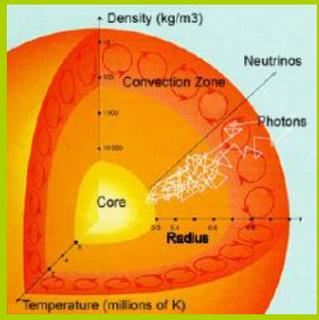
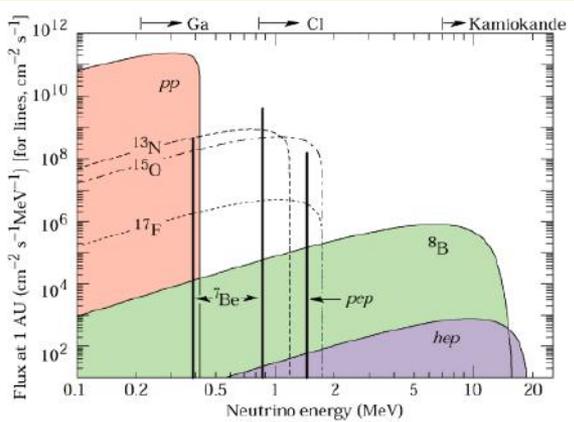
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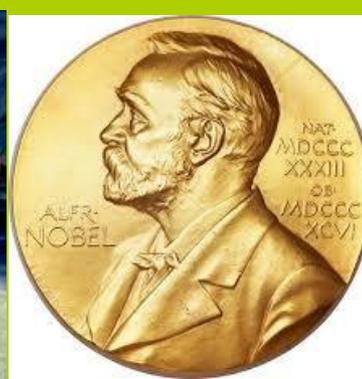
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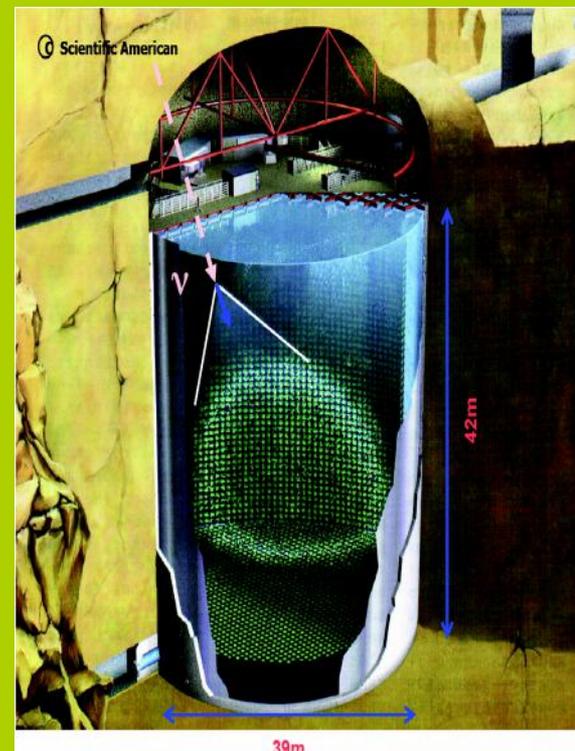
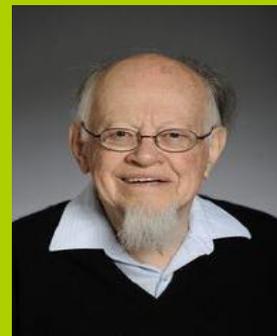
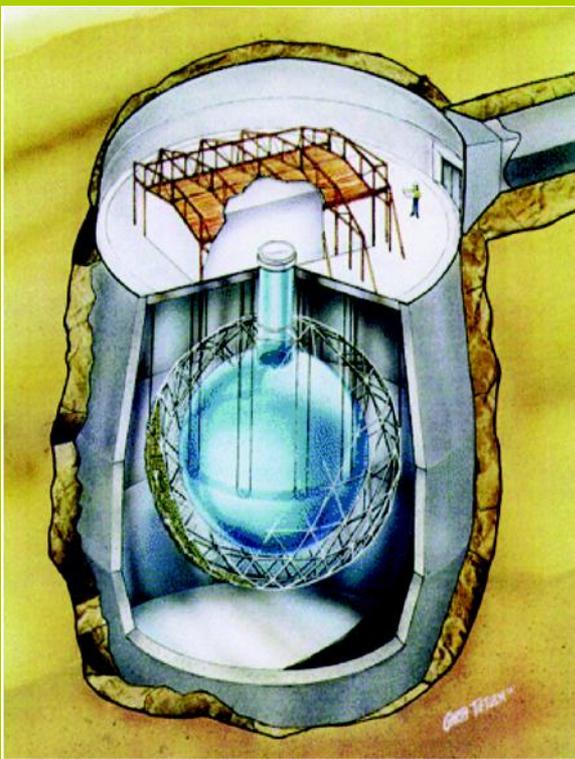
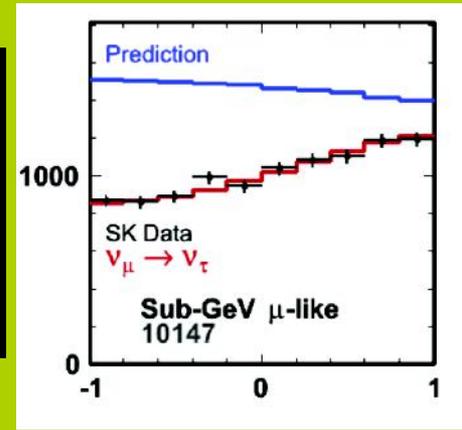
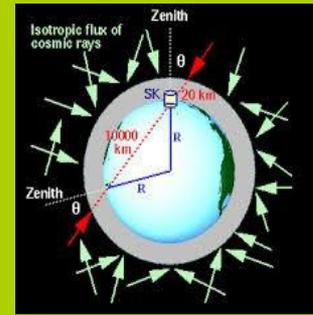
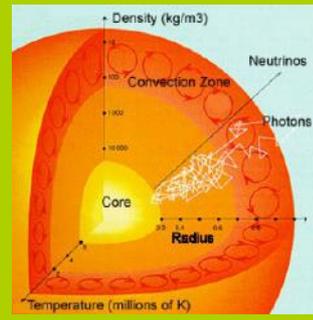
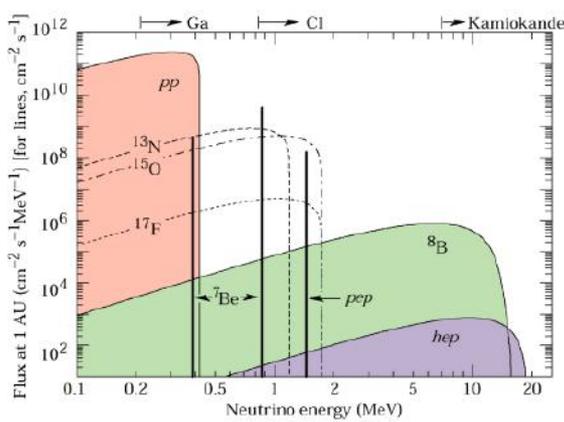
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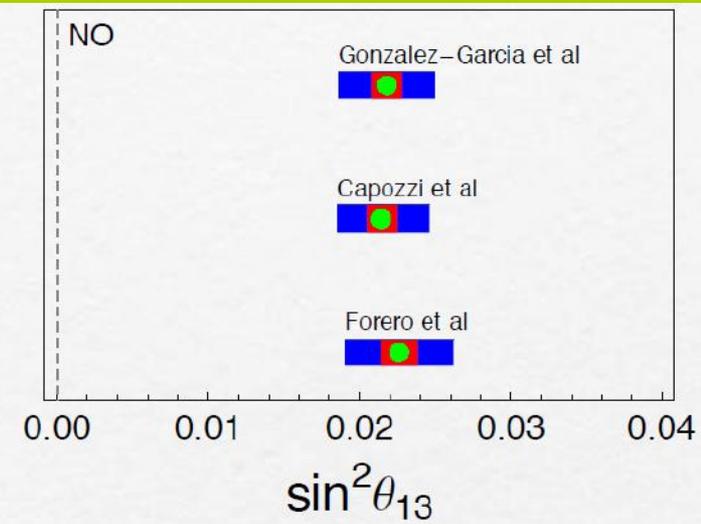
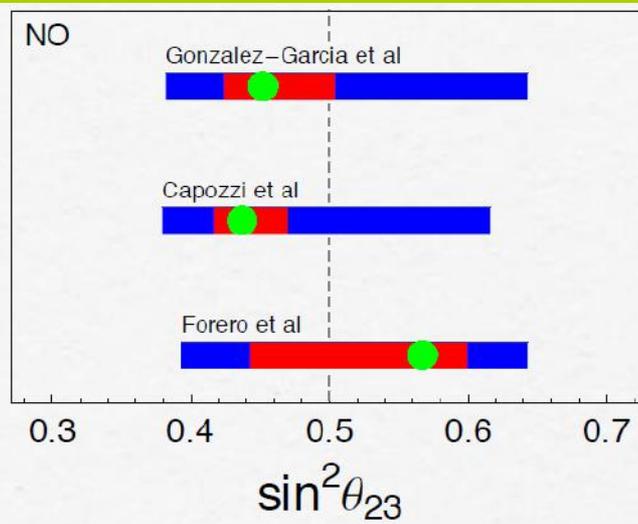
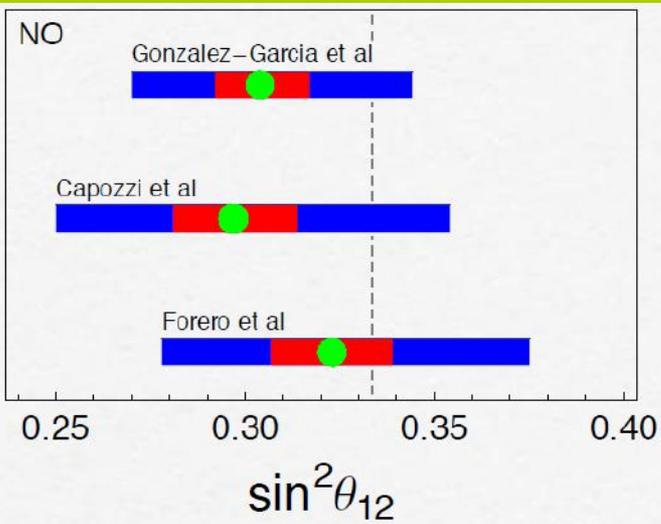
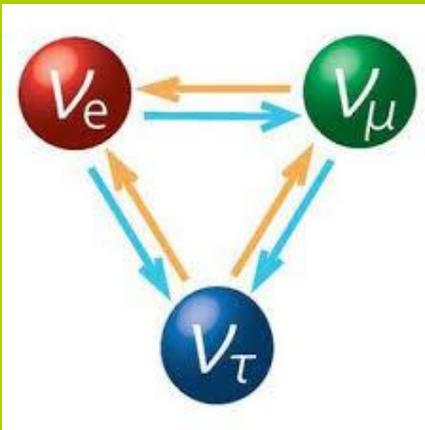
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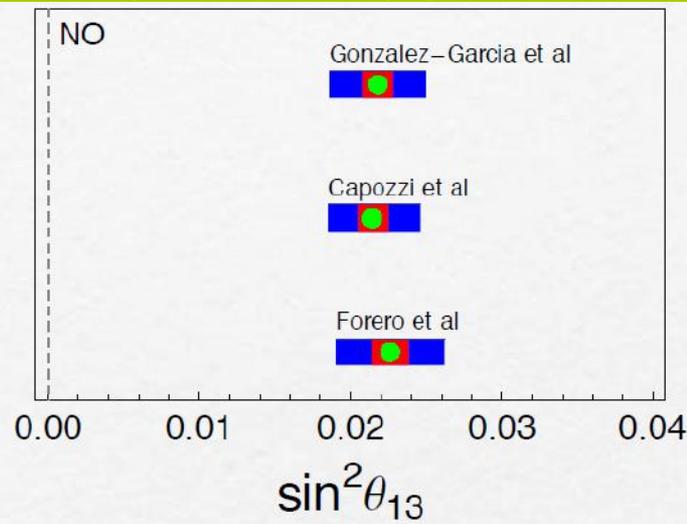
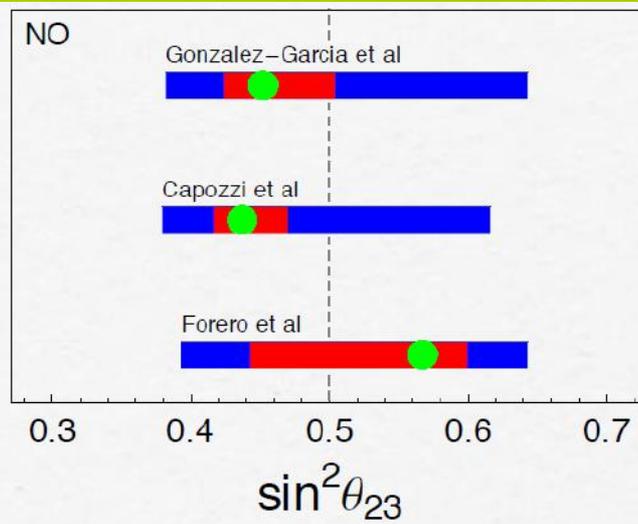
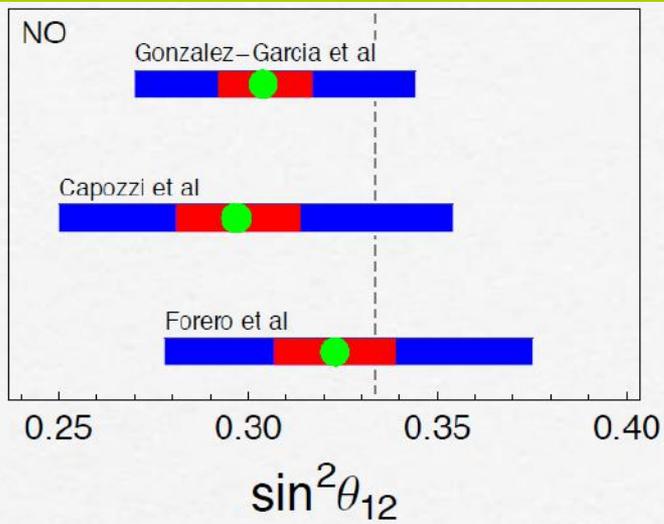
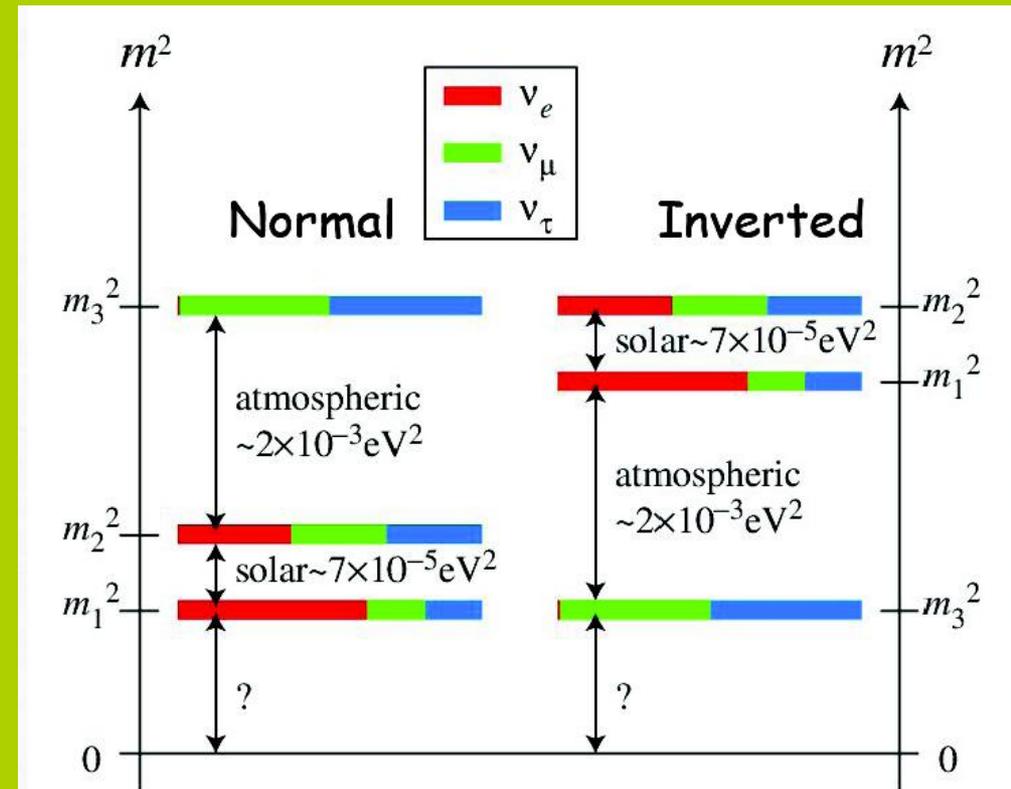
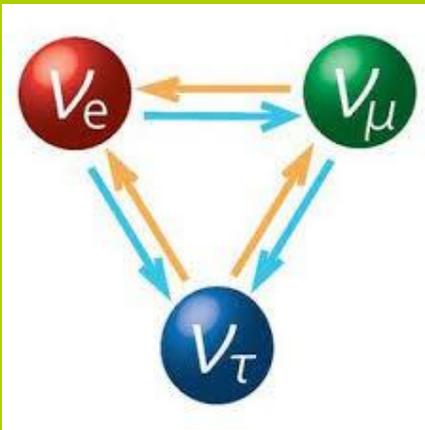
## The Nobel Prize in Physics 2015



# Oscillation parameters



# Oscillation parameters

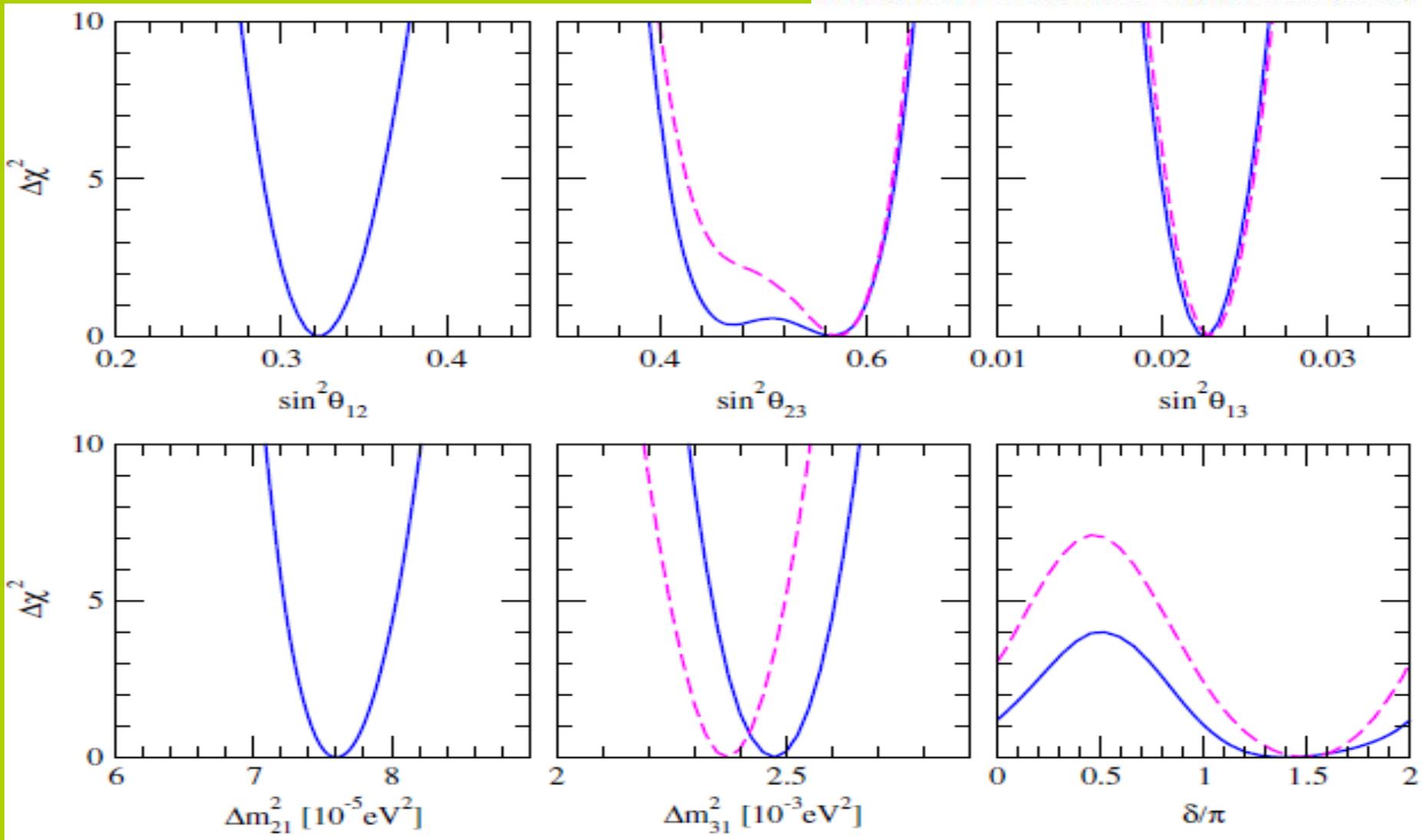




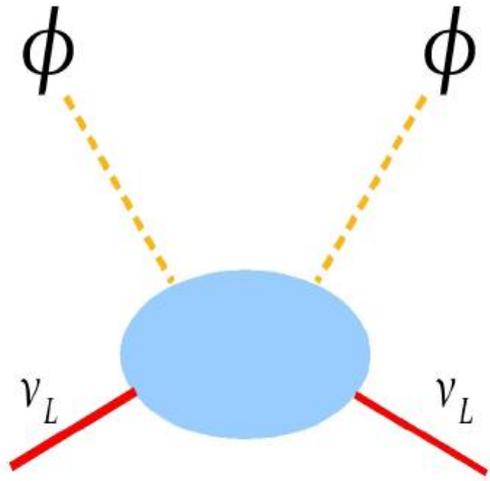
# Oscillation parameters

*Precision era starts*

PHYSICAL REVIEW D 90, 093006 (2014)



# The origin of neutrino mass

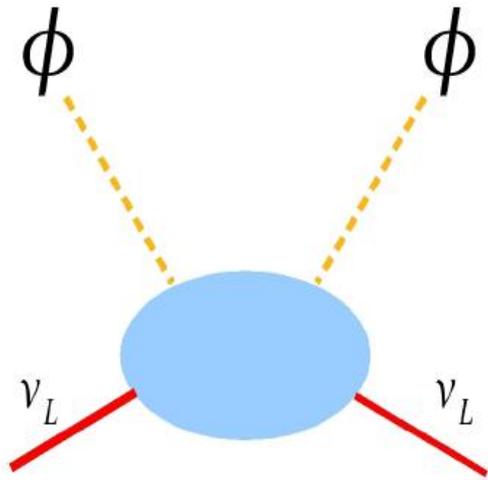


**MECHANISM**

**SCALE**

**FLAVOR STRUCTURE**

# The origin of neutrino mass



**MECHANISM**

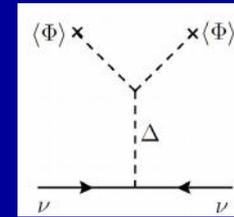
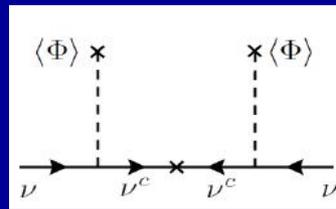
**SCALE**

**FLAVOR STRUCTURE**

# Seesaw

$$v_3 v_1 \sim v_2^2$$

# The origin of neutrino mass

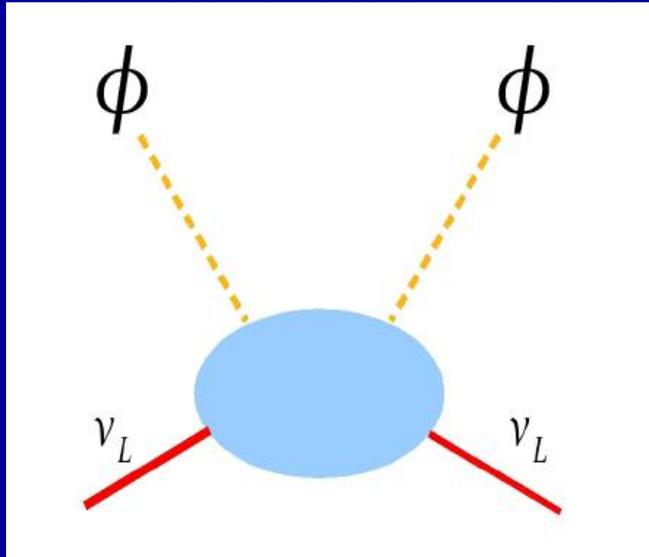


## TYPE I

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

## TYPE II

Schechter-Valle 80/82



# Seesaw

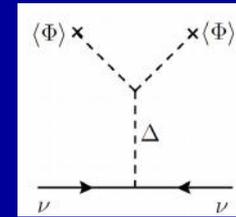
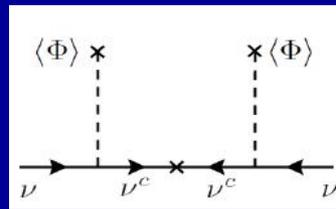
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MECHANISM

SCALE

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# The origin of neutrino mass

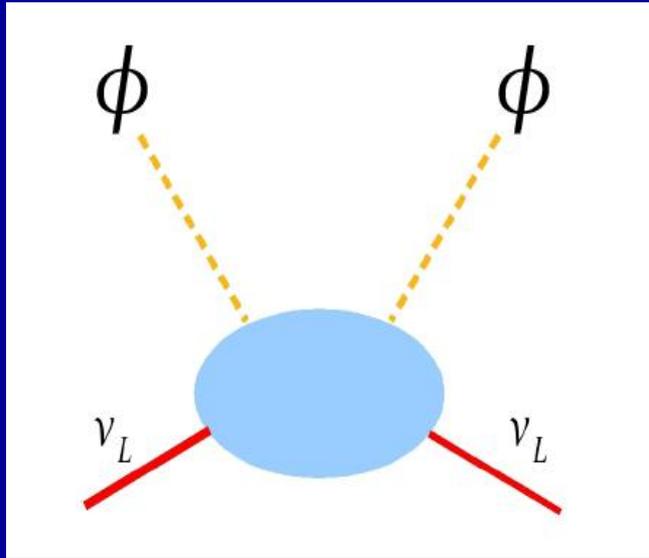


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 Schechter-Valle, 80 & 82

## TYPE II

Schechter-Valle 80/82



# Seesaw

$$v_3 v_1 \sim v_2^2$$

MECHANISM

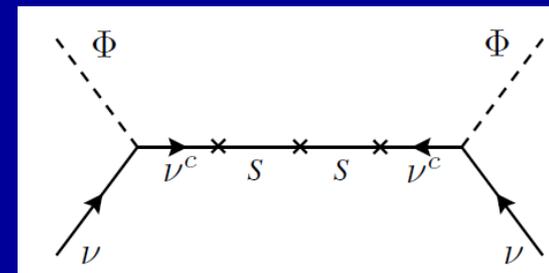
SCALE

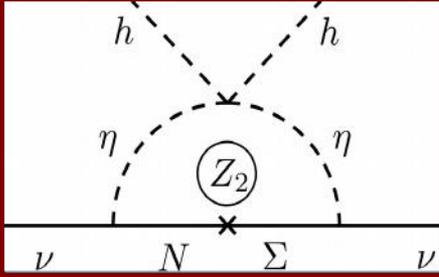
FLAVOR STRUCTURE

Number & properties of messengers

## LOW-SCALE SEESAW

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

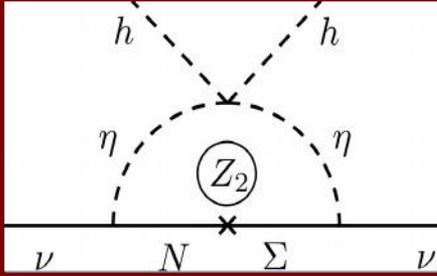




# Radiative neutrino mass

many low-scale neutrino mass schemes ...

arXiv:1404.3751



# Radiative neutrino mass

many low-scale neutrino mass schemes ...

arXiv:1404.3751

**331 electroweak theory** # generations = # colours

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

# Radiative neutrino mass

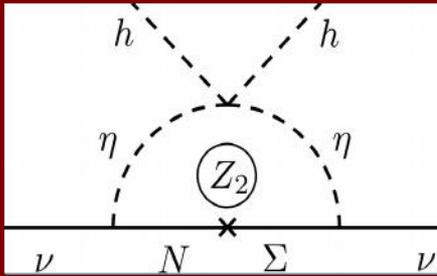
many low-scale neutrino mass schemes ...

arXiv:1404.3751

**331 electroweak theory** # generations = # colours

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

## Gauge vs Higgs



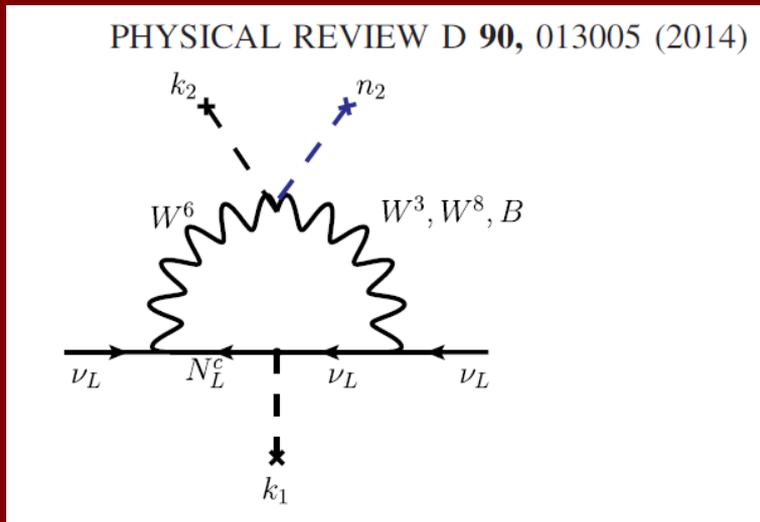
BOUCENNA, MORISI, AND VALLE

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).

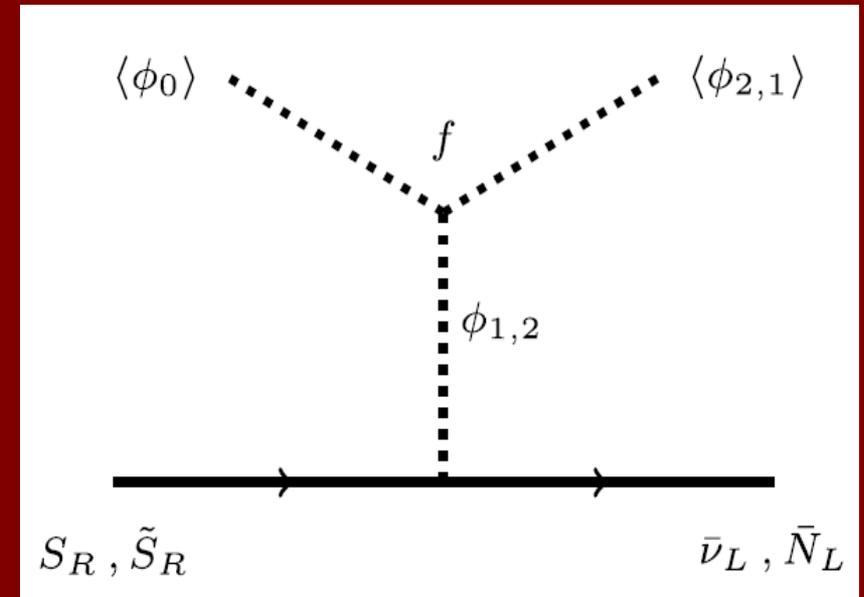
	$\psi_L^\ell$	$\ell_R$	$Q_L^{1,2}$	$Q_L^3$	$\hat{u}_R$	$\hat{d}_R$	$S$	$\phi_1$	$\phi_2$	$\phi_3$
$SU(3)_c$	<b>1</b>	<b>1</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>
$SU(3)_L$	<b>3*</b>	<b>1</b>	<b>3</b>	<b>3*</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>3*</b>	<b>3*</b>	<b>3*</b>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

$$Q = T_3 + \frac{1}{\sqrt{3}}T_8 + X, \quad (2)$$

$$L = \frac{4}{\sqrt{3}}T_8 + \mathcal{L}. \quad (3)$$

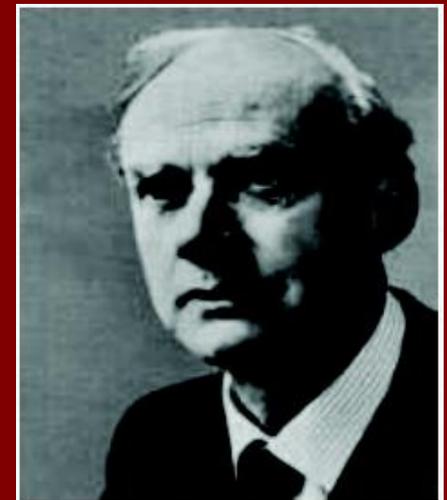


# Type-II Dirac seesaw



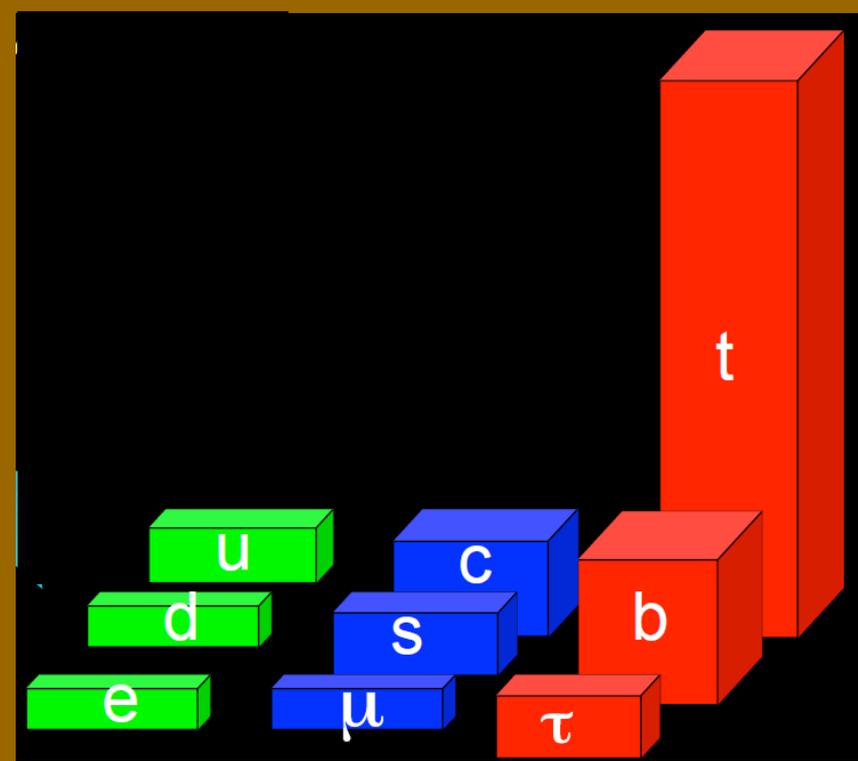
Physics Letters B 755 (2016) 363–366

arXiv:1605.08362



# Flavor puzzle

masses



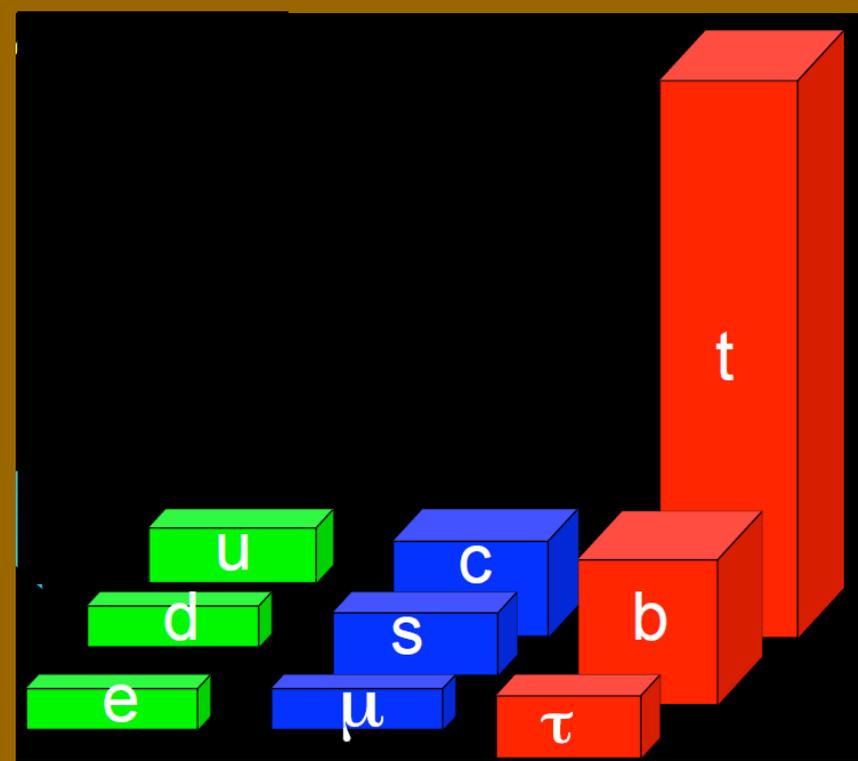
Neutrinos : Lepton number?

mixings

# Flavor puzzle

masses

*b-tau unification*



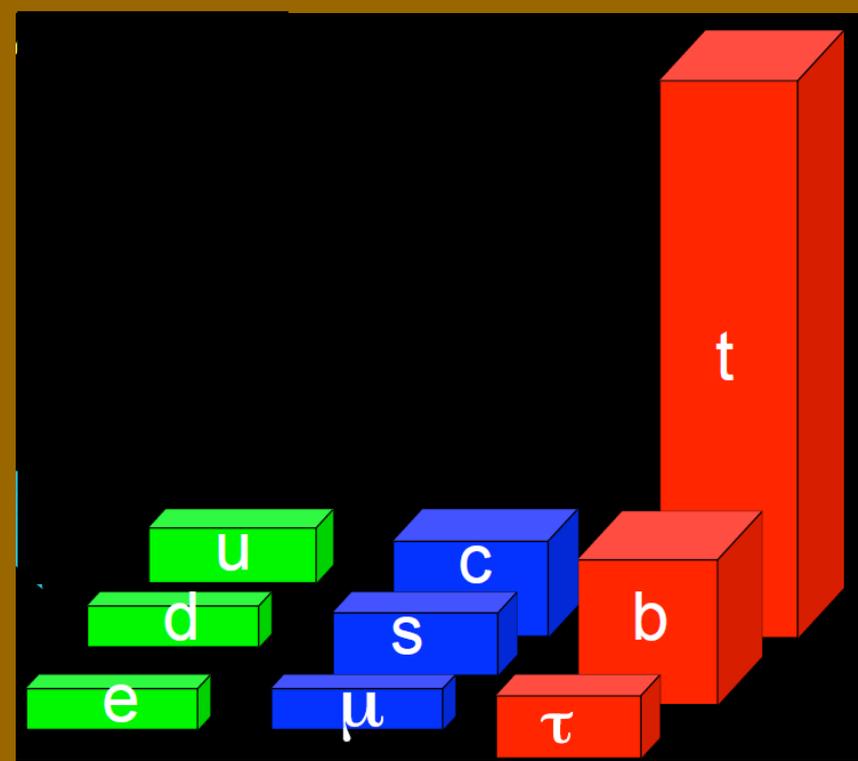
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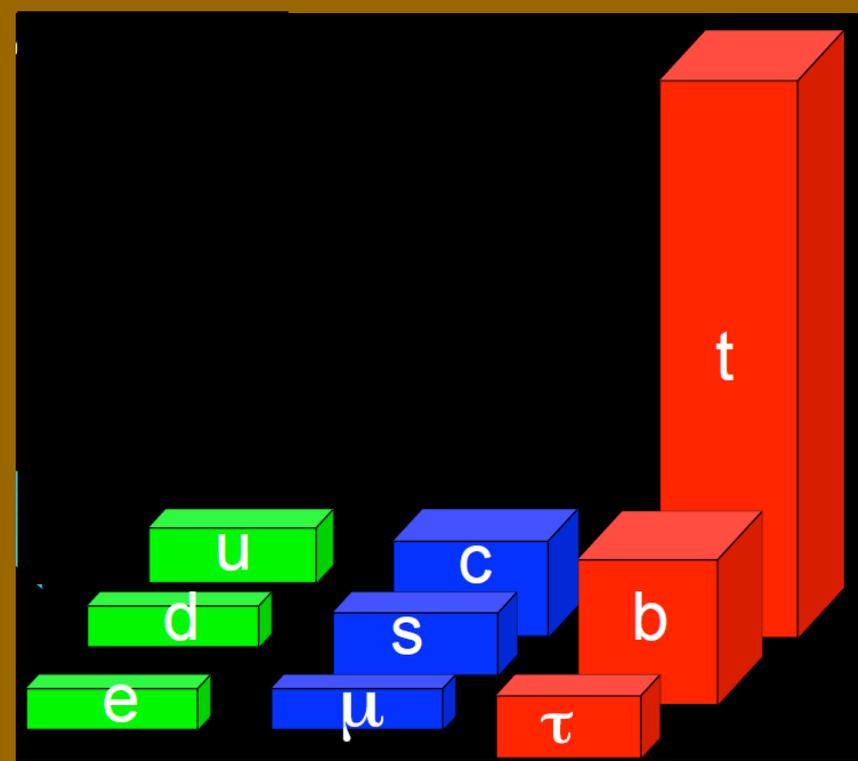
Neutrinos : Lepton number?

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# Flavor puzzle

masses

*b-tau unification*



Neutrinos : Lepton number?

mixings

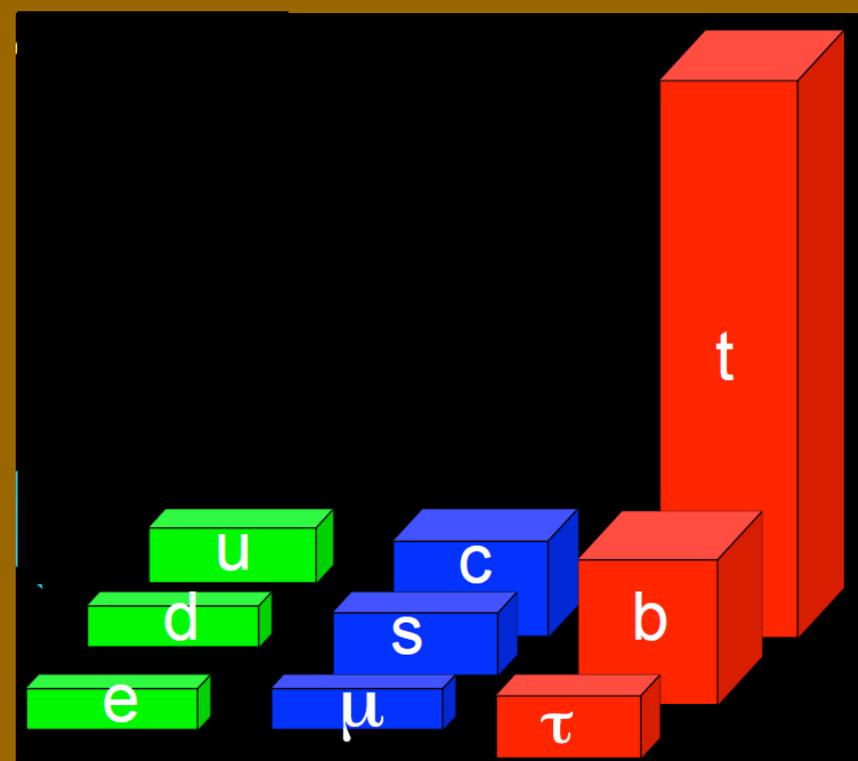
	d	s	b
u	Large yellow square	Small blue square	Very small black square
c	Small green square	Large yellow square	Very small black square
t	Very small black square	Very small black square	Large yellow square

*VS*

	$\nu_1$	$\nu_2$	$\nu_3$
$\nu_e$	Large yellow square	Medium blue square	Small blue square
$\nu_\mu$	Small green square	Medium blue square	Large yellow square
$\nu_\tau$	Small green square	Medium blue square	Large yellow square

# Flavor puzzle

## masses



## *b-tau unification without GUTS*

Neutrinos : Lepton number?

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

## mixings

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

King et al

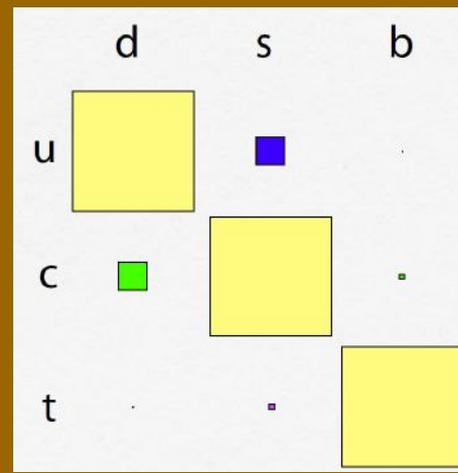
Phys. Lett. B 724 (2013) 68

Morisi et al

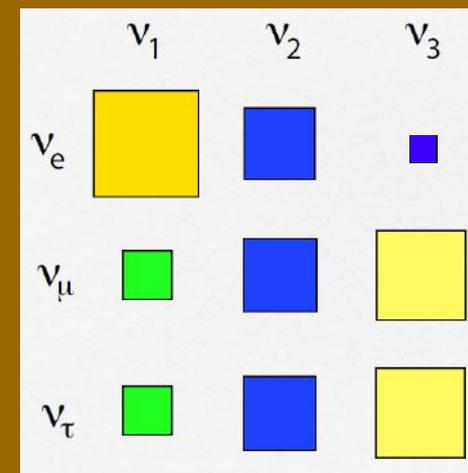
Phys.Rev. D88 (2013) 036001

Bonilla et al

Phys.Lett. B742 (2015) 99

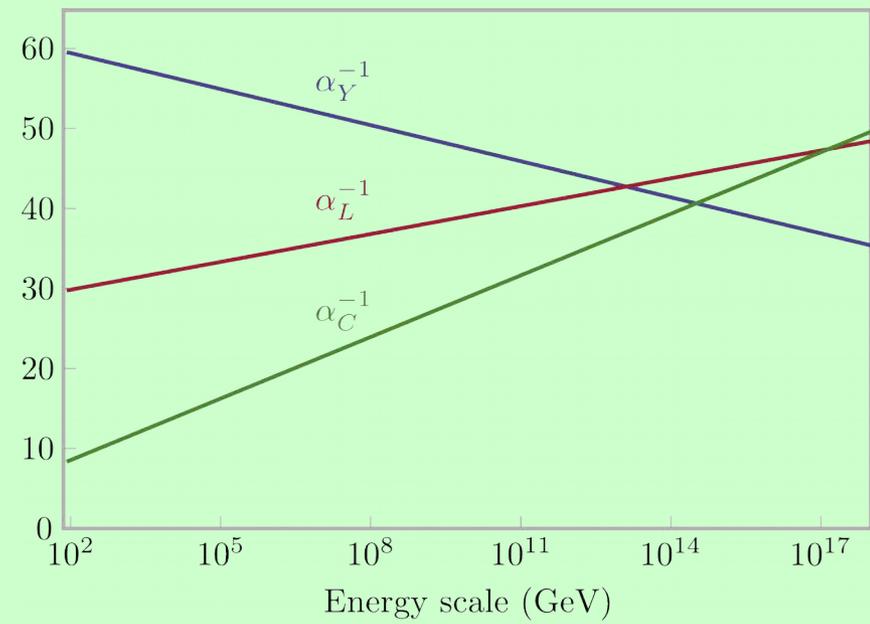


*νs*



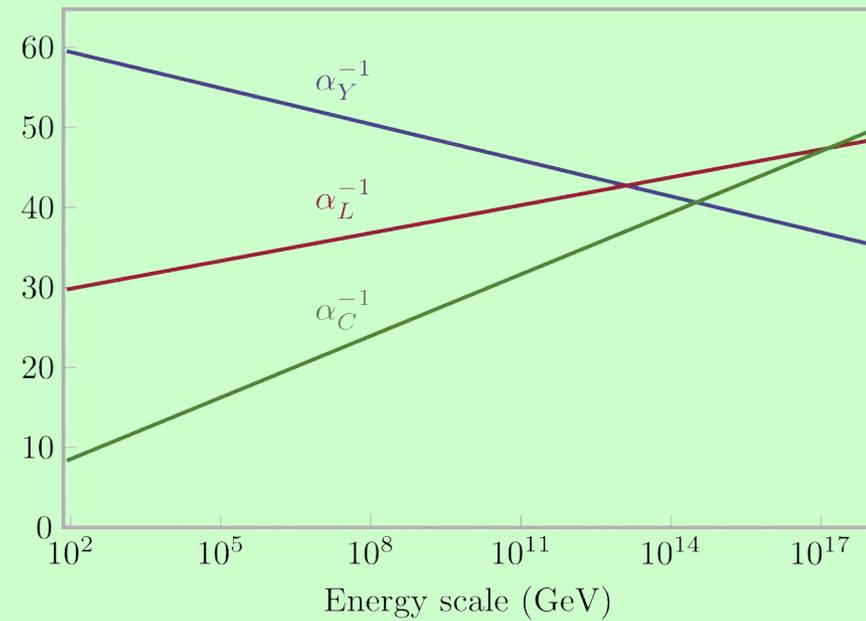
# Gauge coupling unification

*a near miss ...*



# Gauge coupling unification

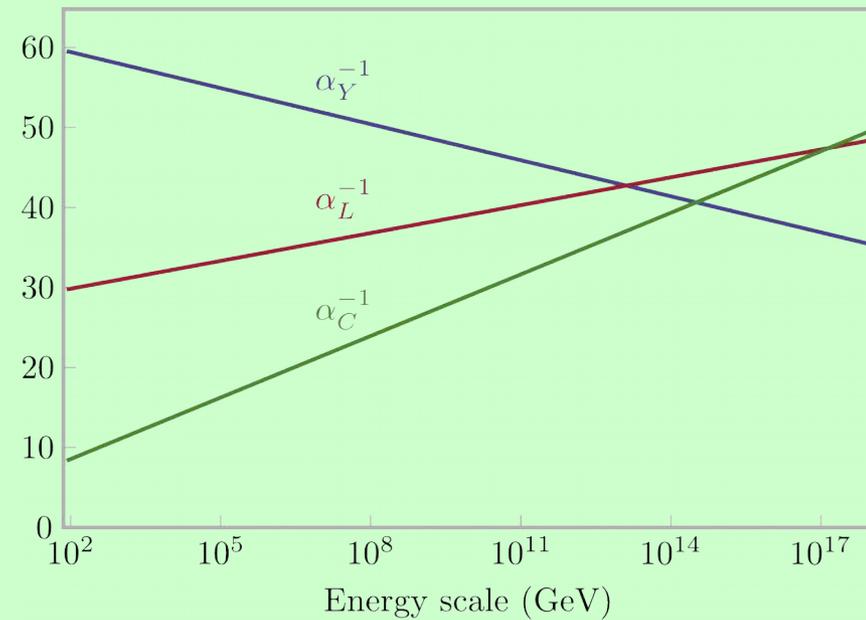
*a near miss ...*



What makes the gauge couplings unify? **GUT (p decay)**  
**SUSY**

# Gauge coupling unification

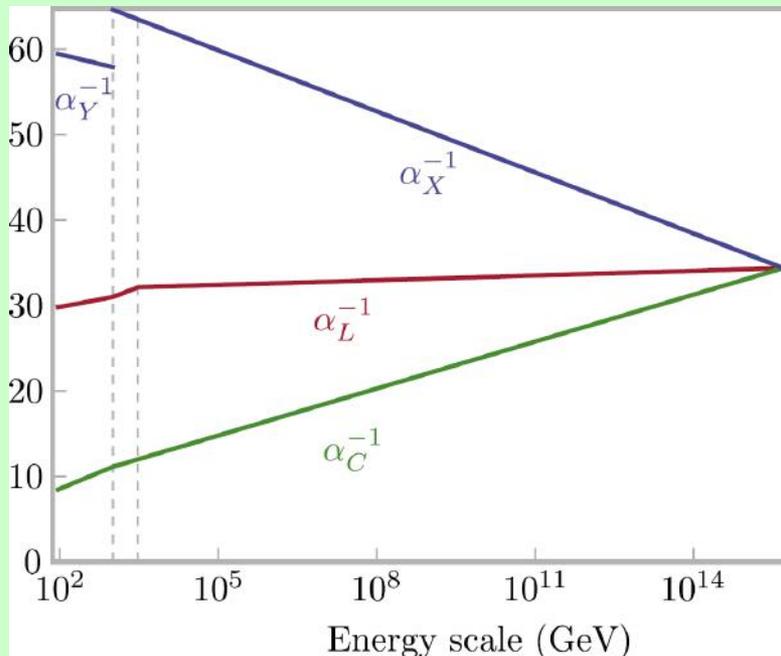
*a near miss ...*



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

SUSY

neutrino



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

Phys. Rev. D 91, 031702 (2015)

Boucenna, Fonseca, Gonzalez-Canales, JV

Valle

# Flavor Symmetry



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

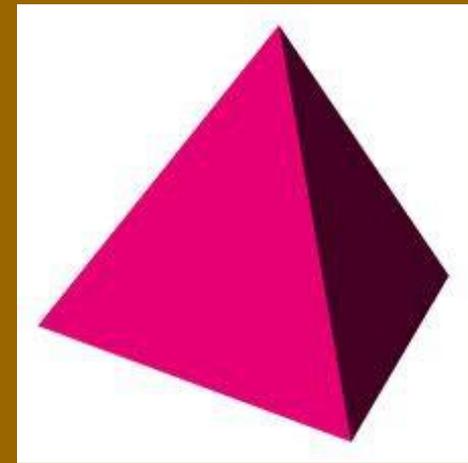
A4

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

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

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

# Flavor Symmetry



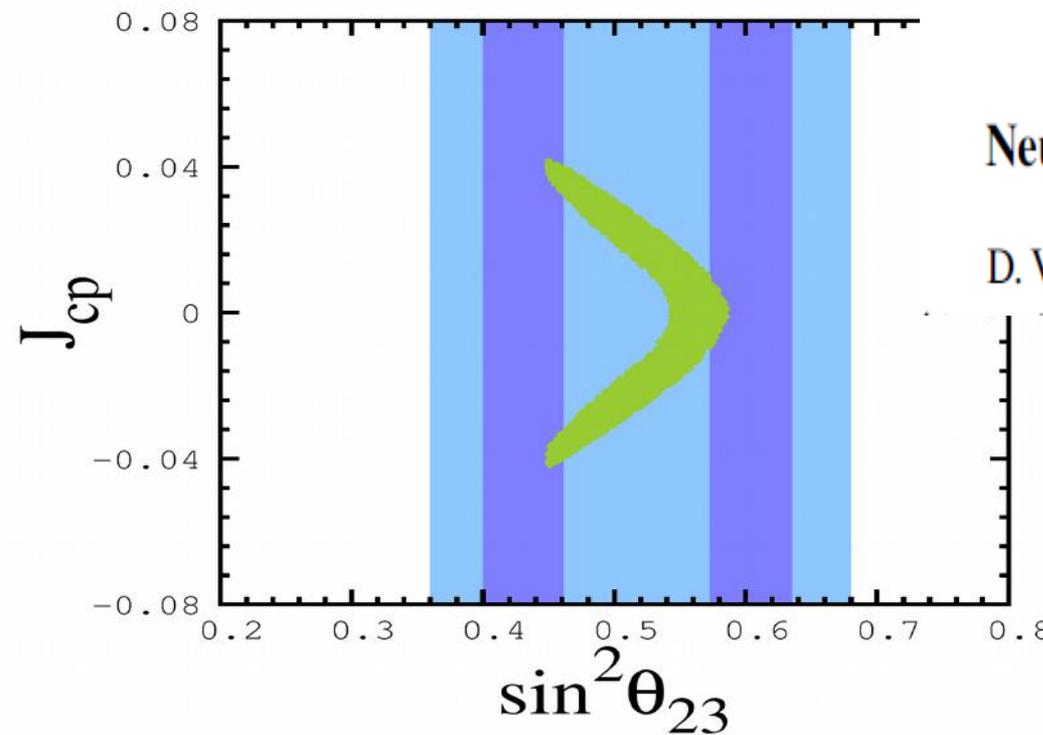
$\begin{pmatrix} \nu_e \\ e \\ e_R \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \\ \mu_R \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \\ \tau_R \end{pmatrix}_L$
$\begin{pmatrix} u \\ d \\ u_R \\ d_R \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \\ c_R \\ s_R \end{pmatrix}_L$	$\begin{pmatrix} t \\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

A4

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

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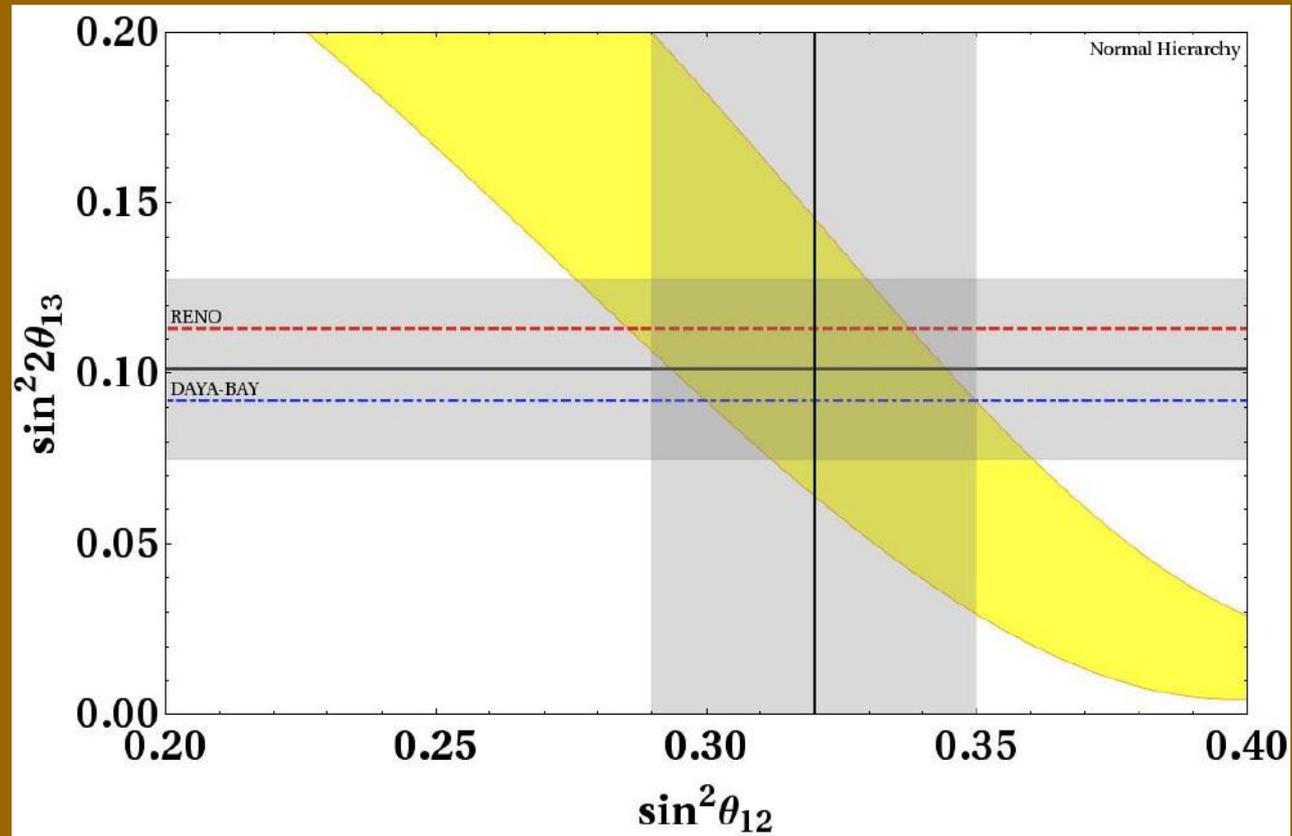
PHYSICAL REVIEW D 88, 016003 (2013)

## Neutrino mixing with revamped A4 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>

# Flavor correlations

Boucenna et al  
PhysRevD.86.073008

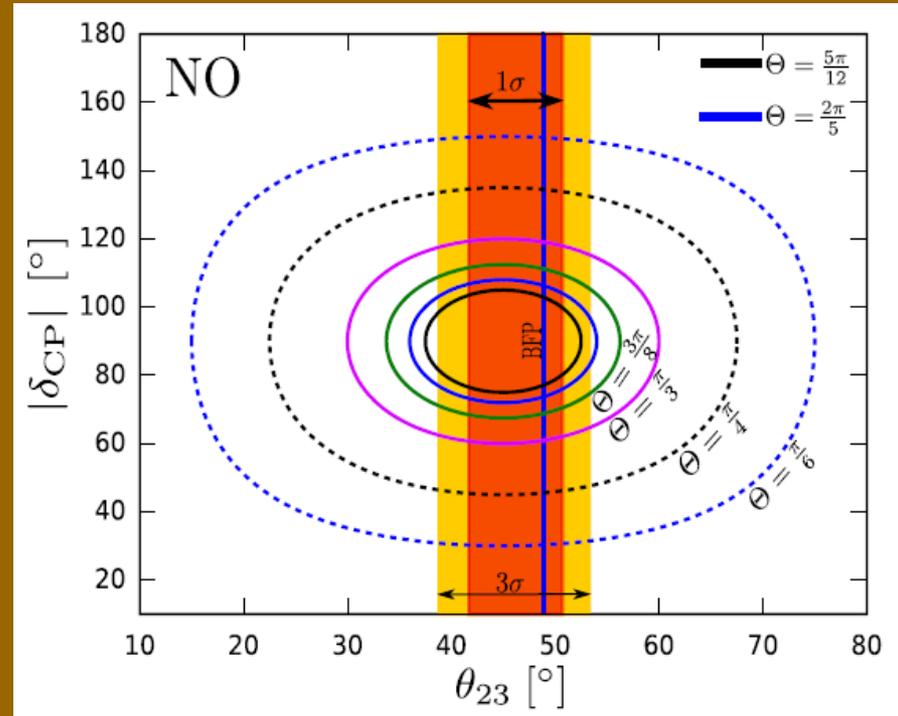


# Model-independent flavor approach

$$\mathbf{X}^T \mathbf{m}_\nu \mathbf{X} = \mathbf{m}_\nu^*$$

*Predicting neutrino mixing  
from residual CP symmetries*

P. Chen et al. / Physics Letters B 753 (2016) 644–652



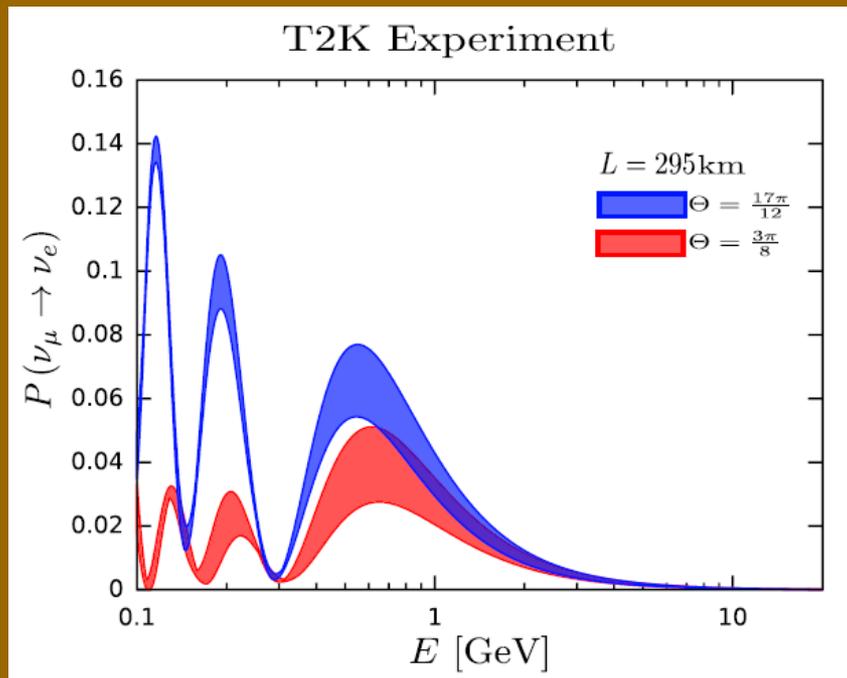
# Model-independent flavor approach

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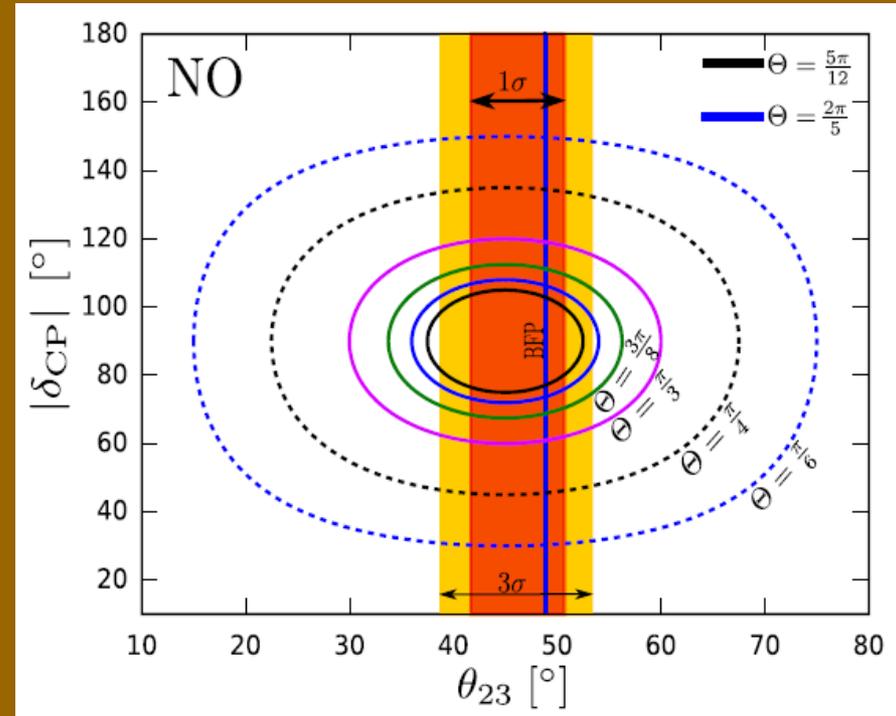


*Predicting neutrino mixing  
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P. Chen et al. / Physics Letters B 753 (2016) 644–652

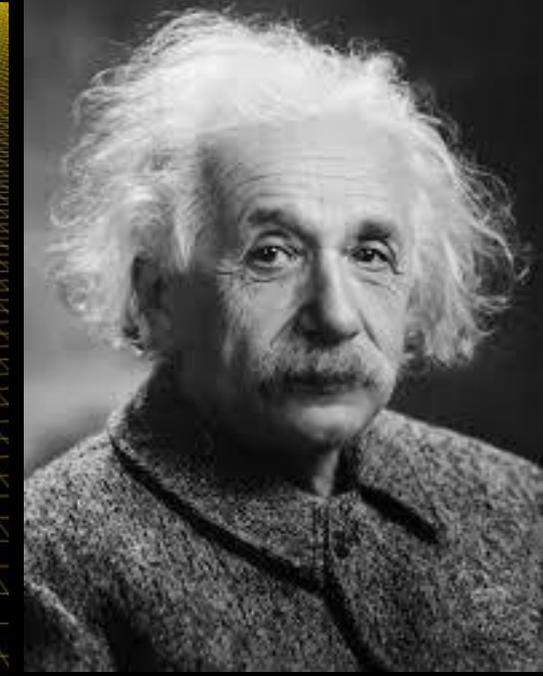
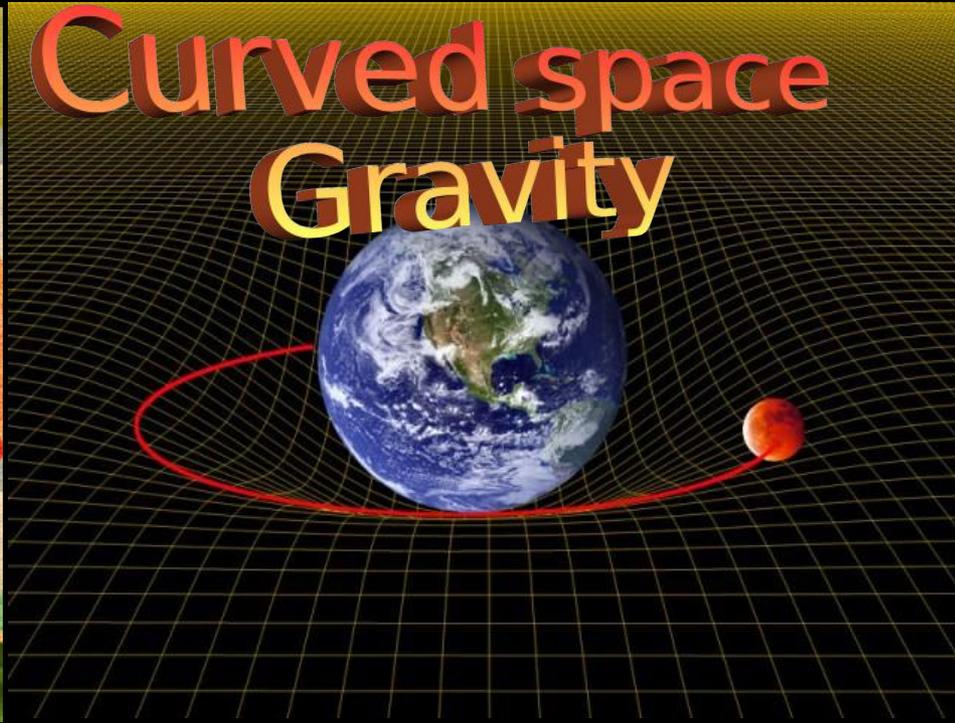
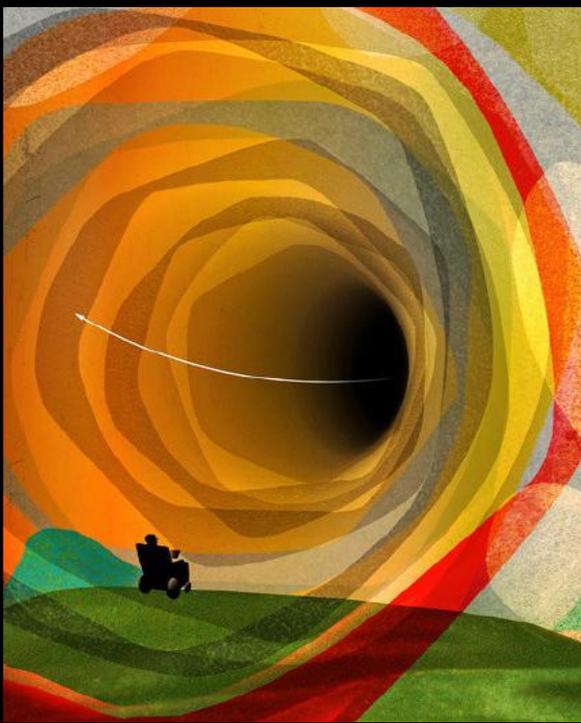


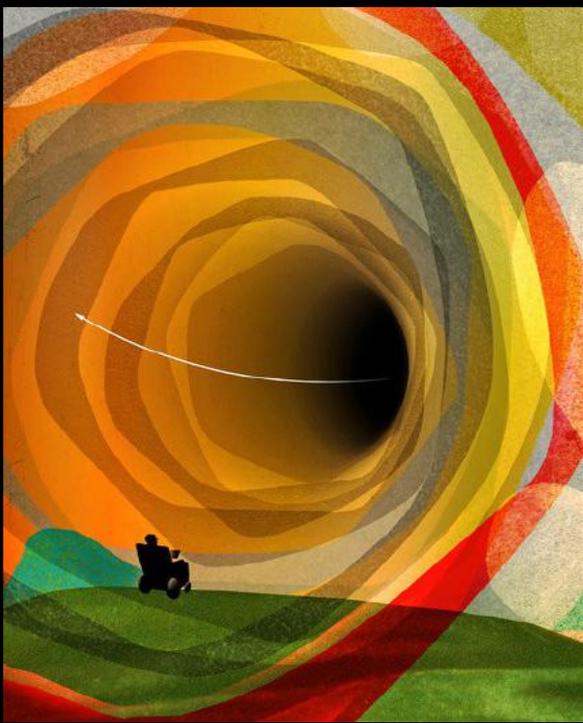
NOVA, DUNE



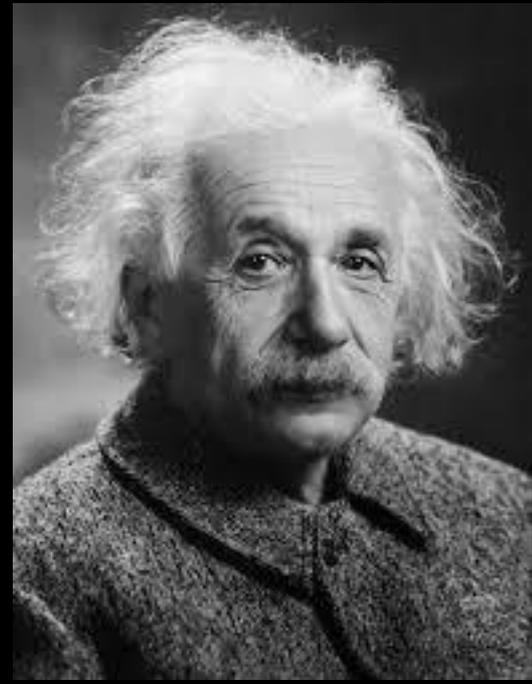


How about gravity?

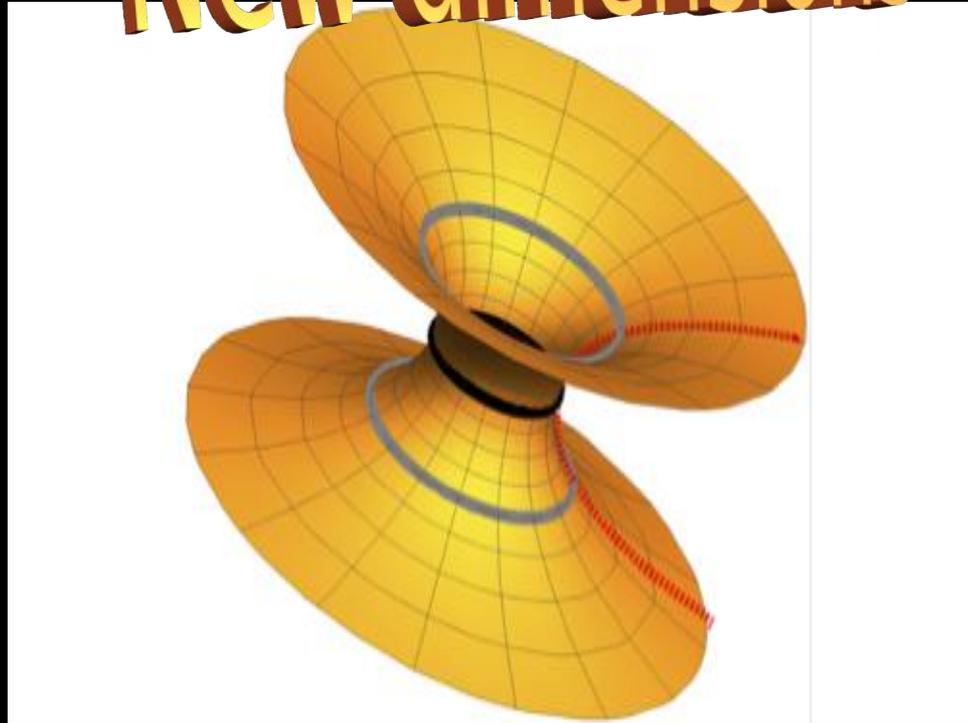




# Curved space Gravity



# New dimensions



# Warped flavor

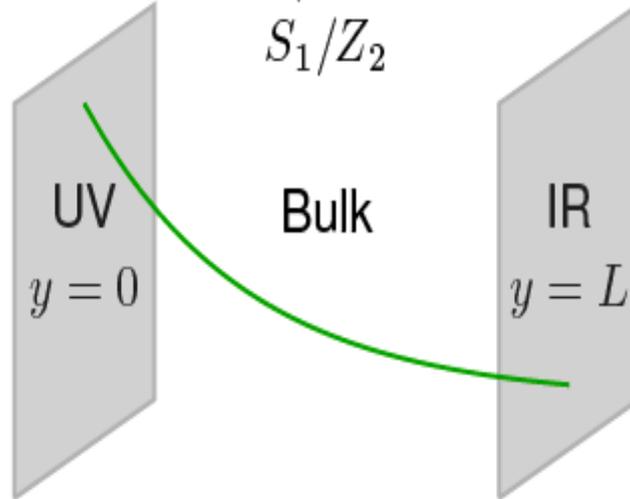
Chen et al arXiv:1509.06683

JHEP01(2016)007

## Randall-Sundrum brane-world

$$ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$$

$S_1/Z_2$



5D field theory on a slice of  $AdS_5$

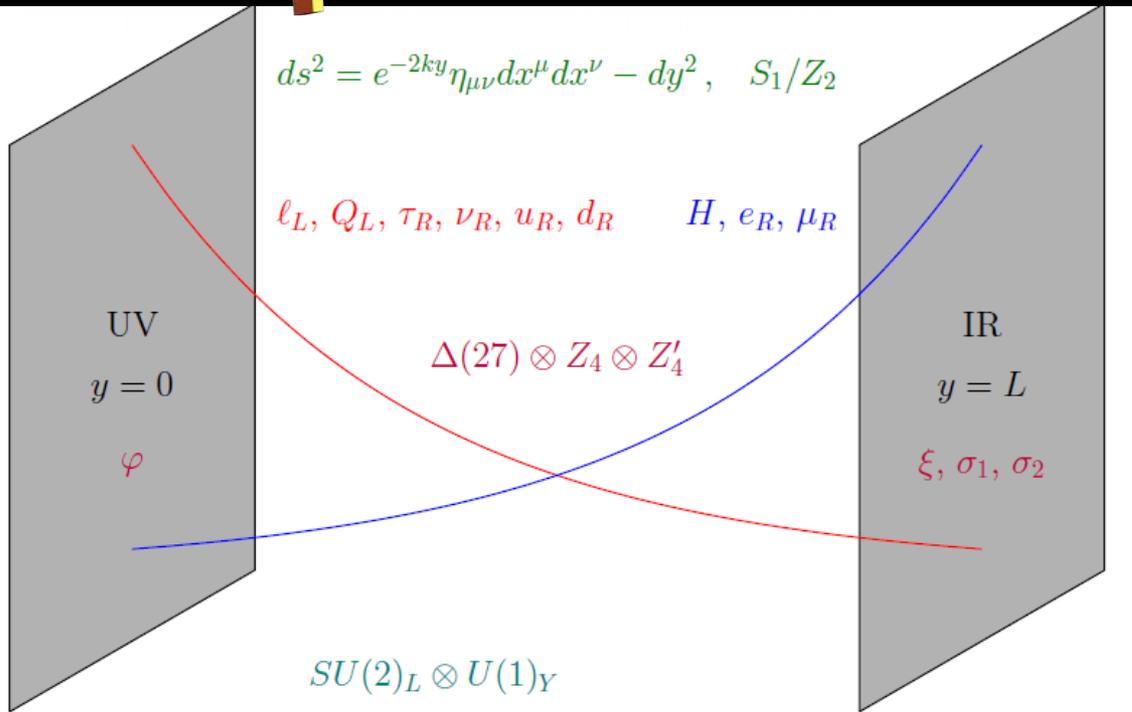
Energy scales warped down as one approaches IR

Localizing the Higgs at the IR brane and setting  $kL \simeq 35$  explains the smallness of the EW scale!

# Warped flavor

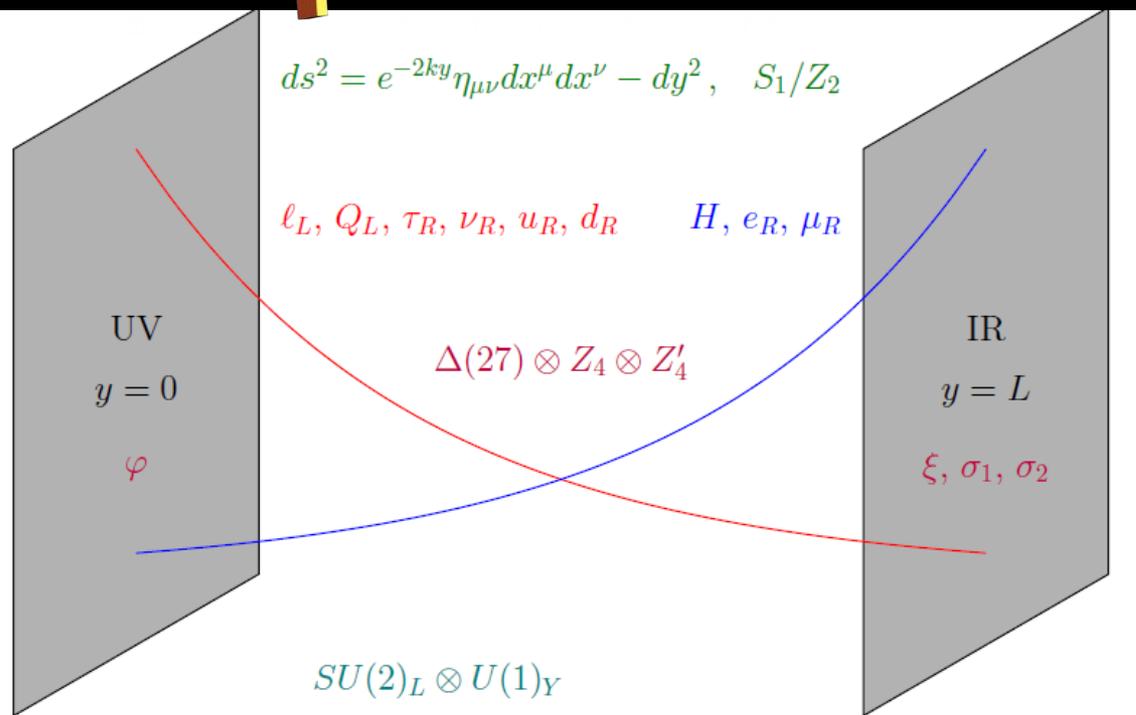
Chen et al arXiv:1509.06683

JHEP01(2016)007



Mass hierarchies in principle accounted for by judicious bulk parameter choices

# Warped flavor



Mass hierarchies in principle accounted for by judicious bulk parameter choices

$$\sin^2 \theta_{12} \cos^2 \theta_{13} = 1/3$$

4 neutrino mixing angles & CP phase in terms of 2

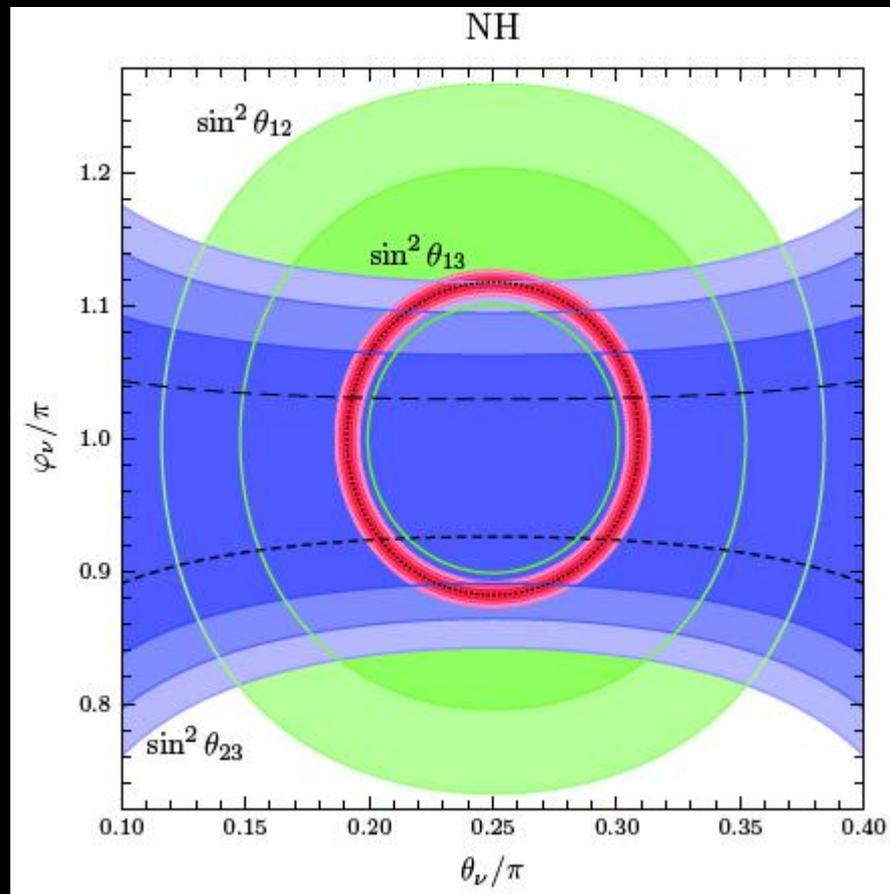
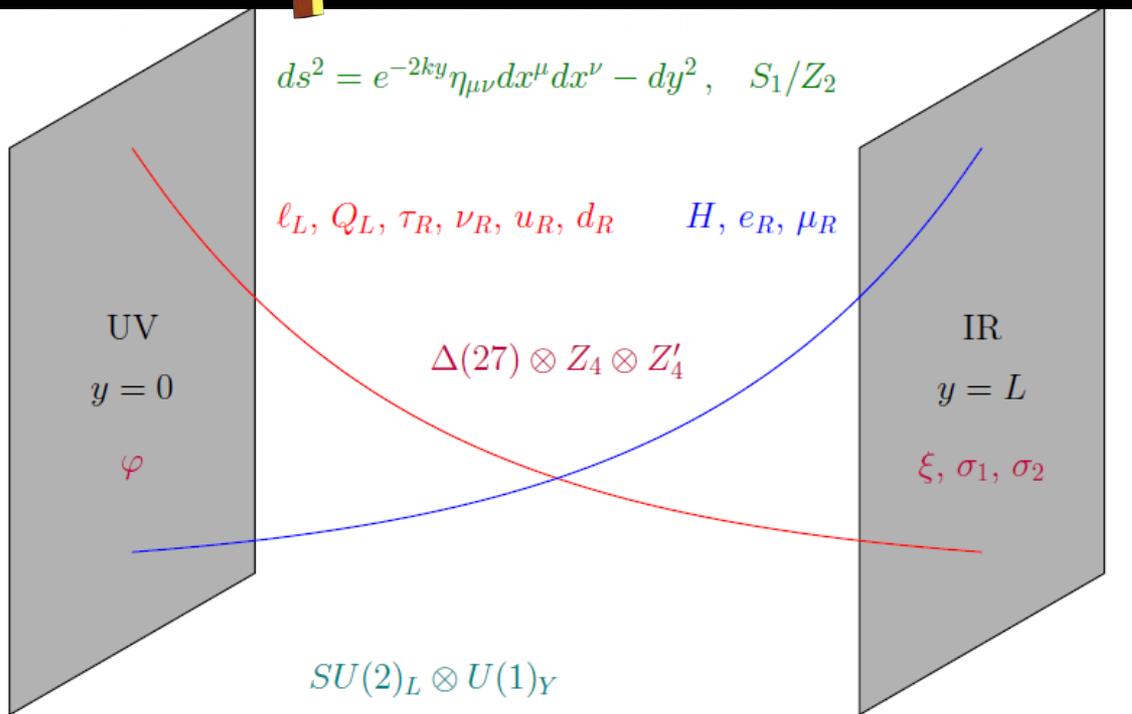
$$\sin^2 \theta_{23} = \frac{1 - \sin 2\theta_\nu \sin(\pi/6 - \varphi_\nu)}{2 - \sin 2\theta_\nu \cos \varphi_\nu}$$

$$J_{\text{CP}} = -\frac{1}{6\sqrt{3}} \cos 2\theta_\nu .$$

# Warped flavor

Chen et al arXiv:1509.06683

JHEP01(2016)007



Mass hierarchies in principle accounted for by judicious bulk parameter choices

$$\sin^2 \theta_{12} \cos^2 \theta_{13} = 1/3$$

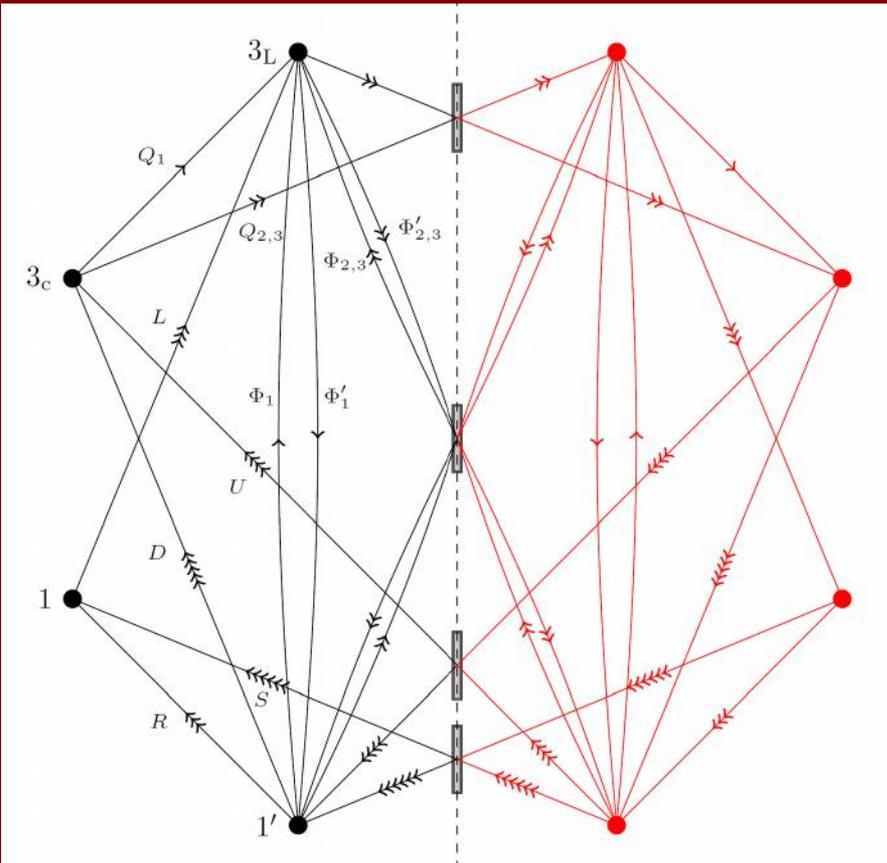
4 neutrino mixing angles & CP phase in terms of 2

$$\sin^2 \theta_{23} = \frac{1 - \sin 2\theta_\nu \sin(\pi/6 - \varphi_\nu)}{2 - \sin 2\theta_\nu \cos \varphi_\nu}$$

$$J_{\text{CP}} = -\frac{1}{6\sqrt{3}} \cos 2\theta_\nu .$$

# String completion of 331

Addazi et al Phys.Lett. B759 (2016) 471-478



string completion of EW model with **No** conventional GUT embedding

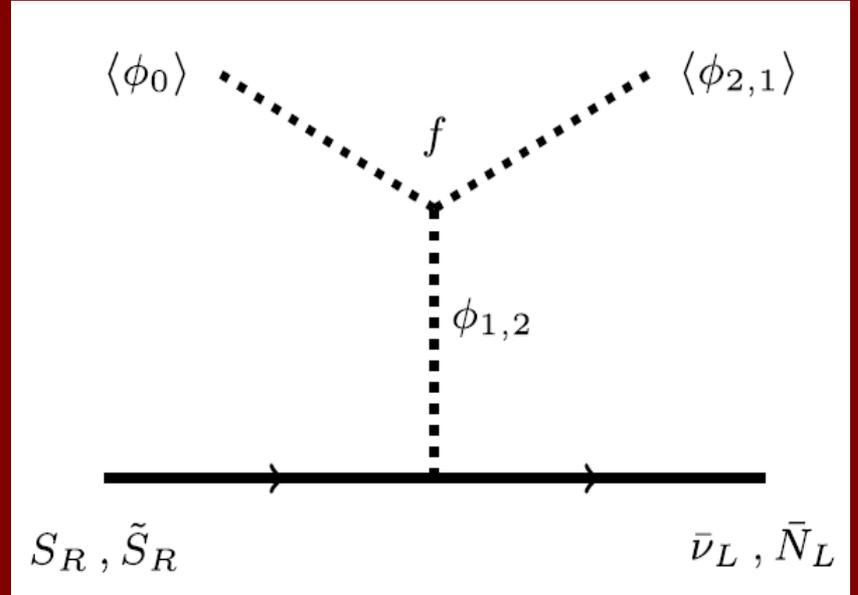
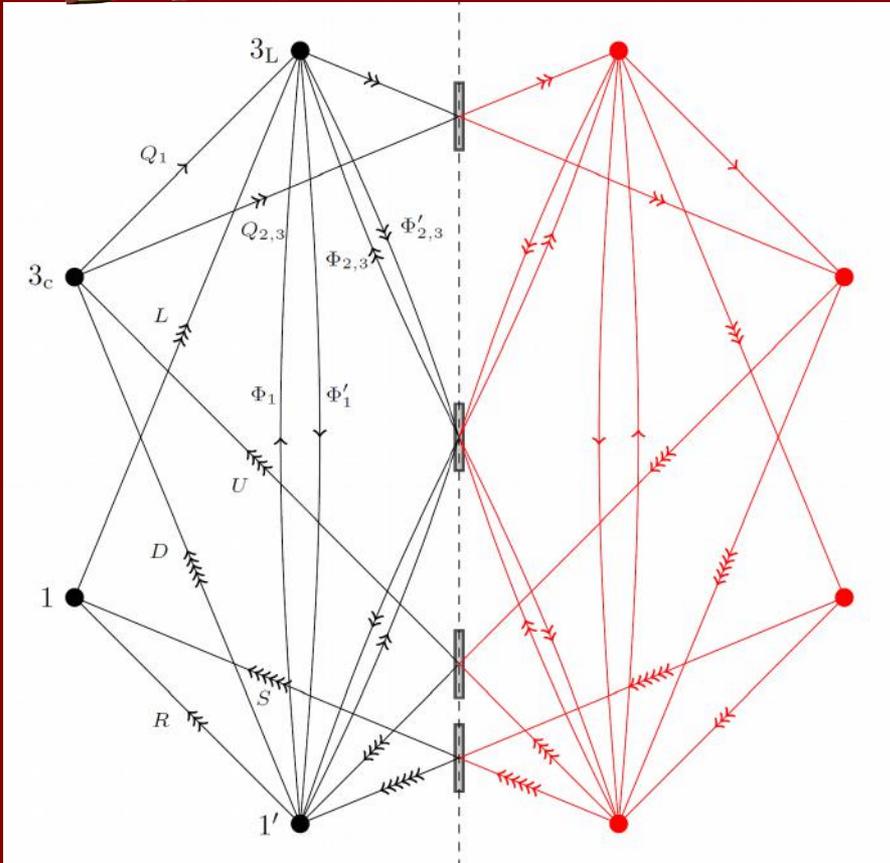
Quiver set-up free of gauge and string anomalies **iff** extra RH states

**no**  $p$  decay, **no** RPV ...

**neutron-antineutron oscillations** added from exotic instantons

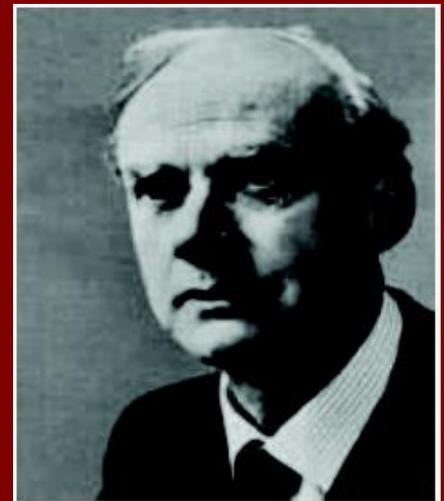
# Dirac seesaw

# From strings

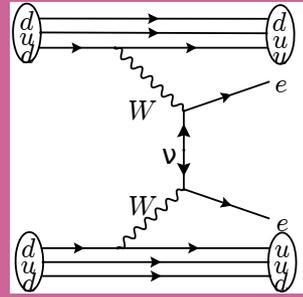
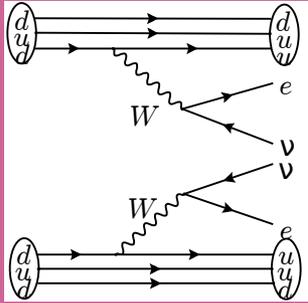


Physics Letters B 755 (2016) 363–366

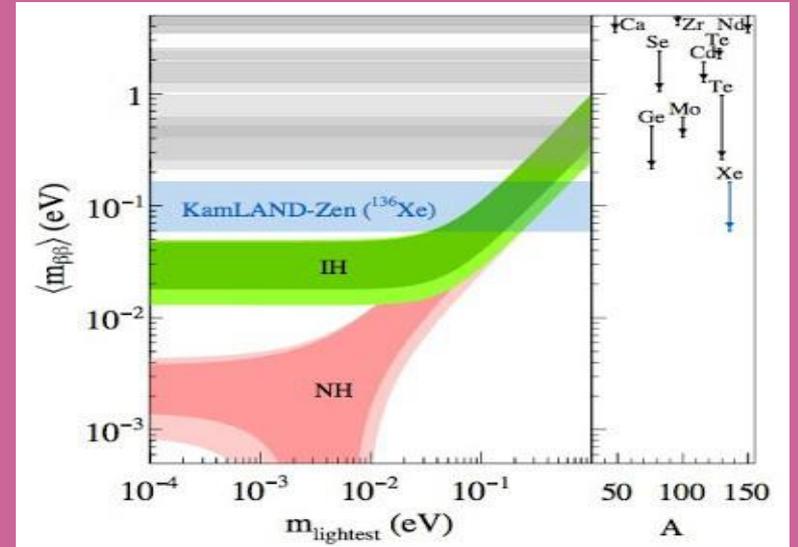
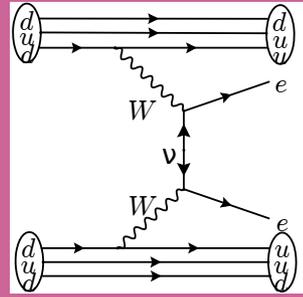
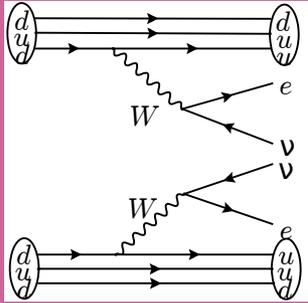
arXiv:1605.08362



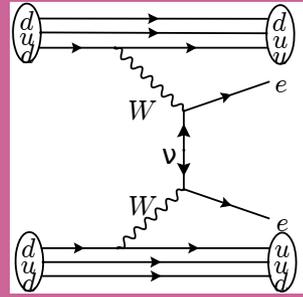
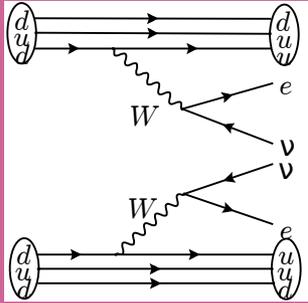
# Neutrinoless double beta decay



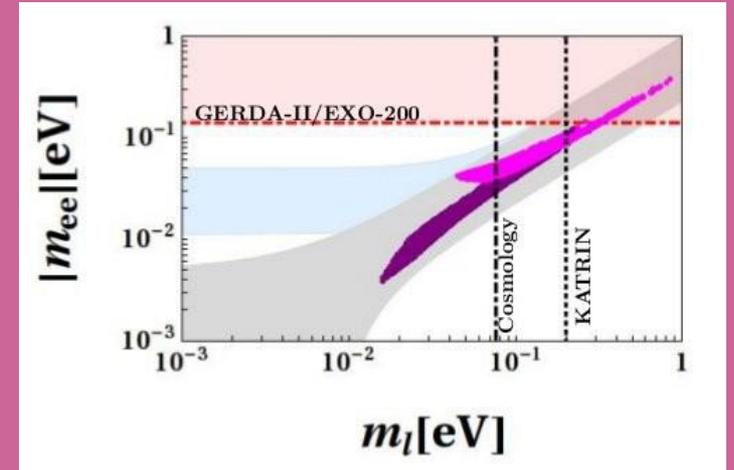
# Neutrinoless double beta decay



# Neutrinoless double beta decay

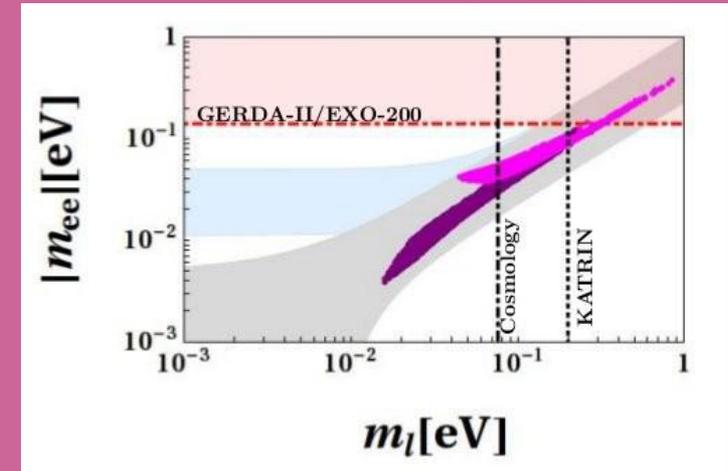
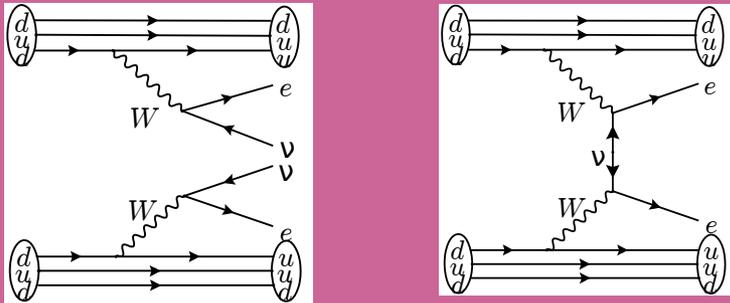


## Flavor Sensitivity



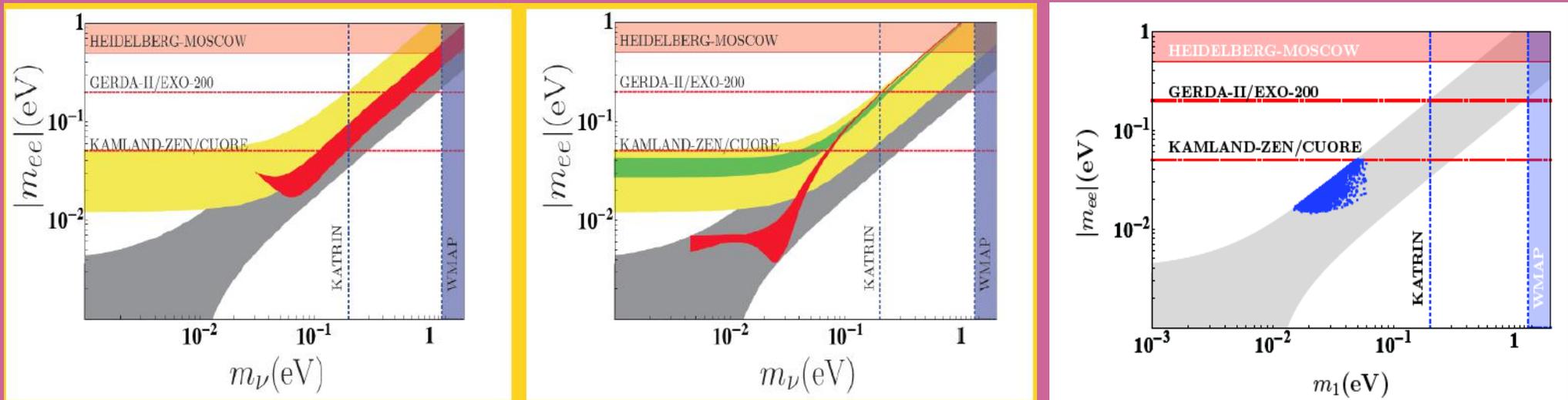
Bonilla et al arXiv:1411.4883

# Neutrinoless double beta decay



Bonilla et al arXiv:1411.4883

## Flavor Sensitivity



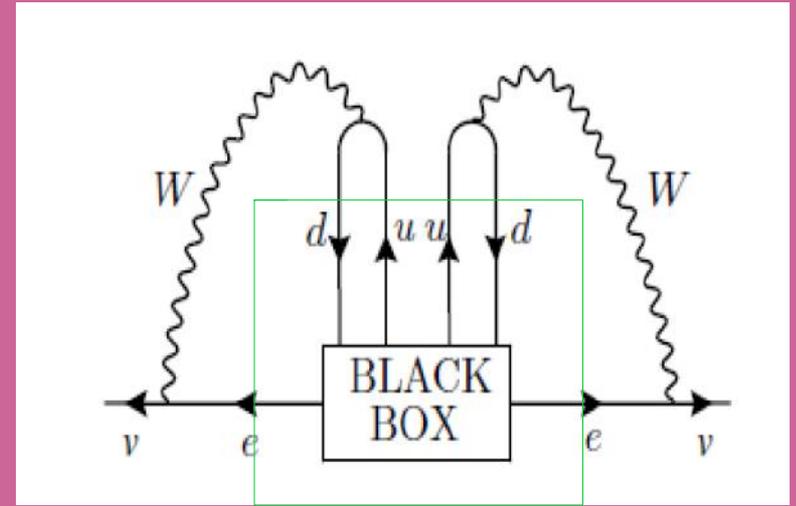
Dorame et al  
NPB861 (2012) 259-270

Valle  
PhysRevD.86.056001

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



# The Black Box



Schechter, JWFV 82

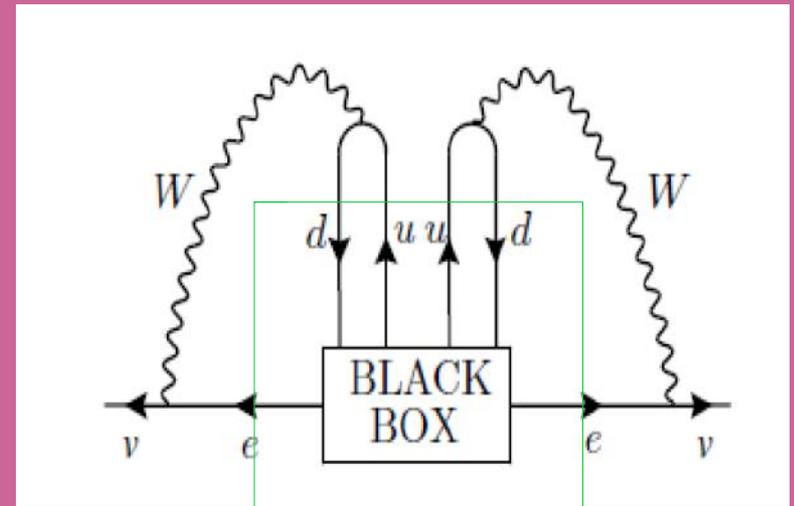
Lindner et al JHEP 1106 (2011) 091



# The Black Box

*Even if mediated by  
short-range mechanism ...*

*Heavy mediators at the LHC*



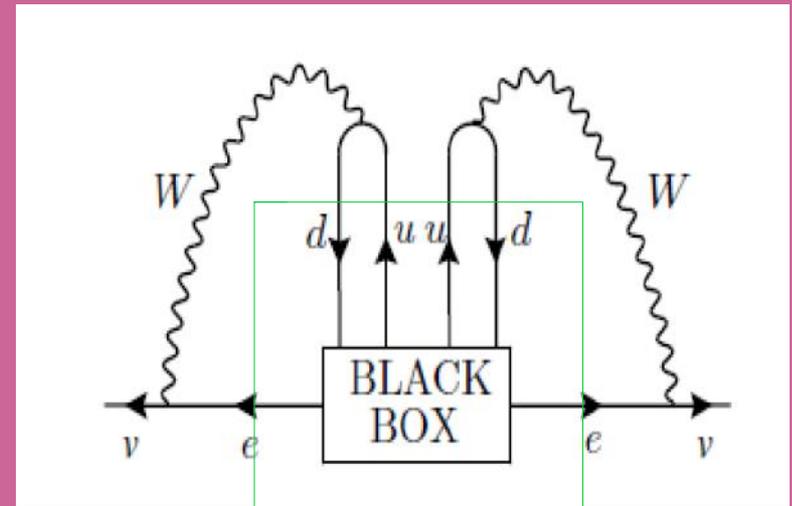
Schechter, JWFV 82

Lindner et al JHEP 1106 (2011) 091



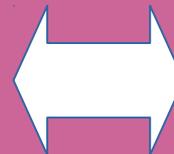
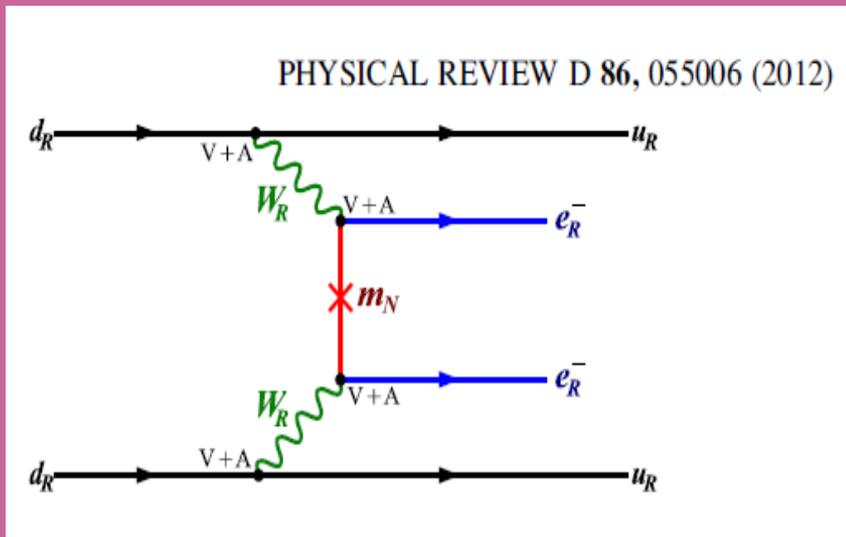
# The Black Box

*Even if mediated by short-range mechanism ...*

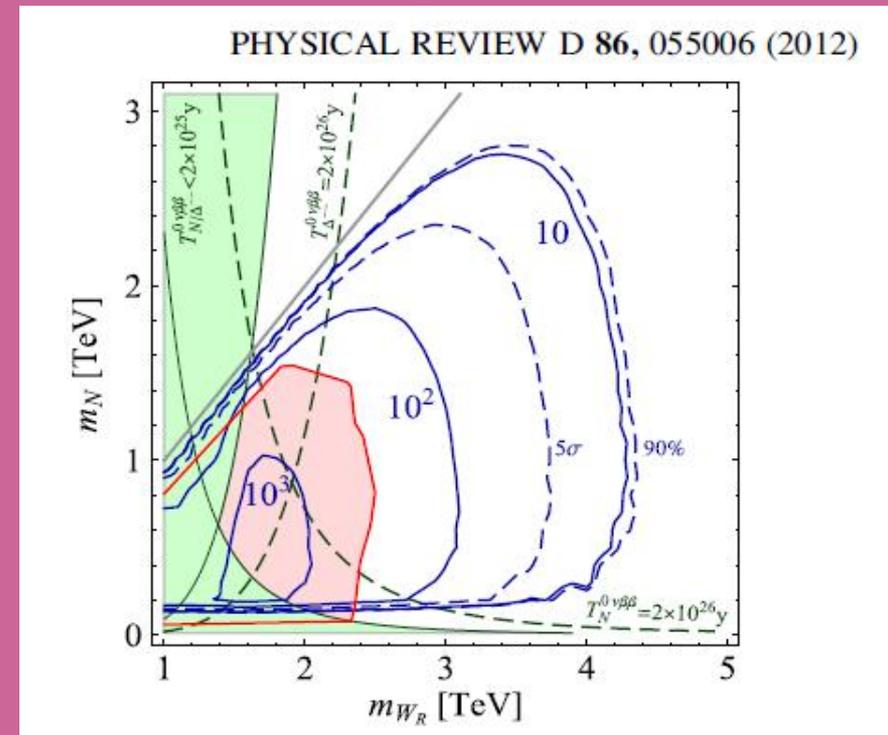


Schechter, JWFV 82  
Lindner et al JHEP 1106 (2011) 091

## Heavy mediators at the LHC



Valle

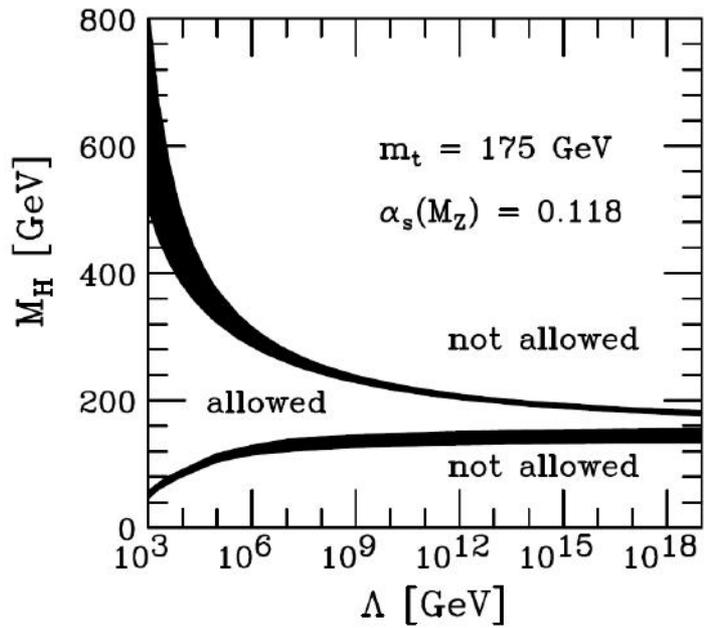




SM vacuum

Valle

# SM vacuum

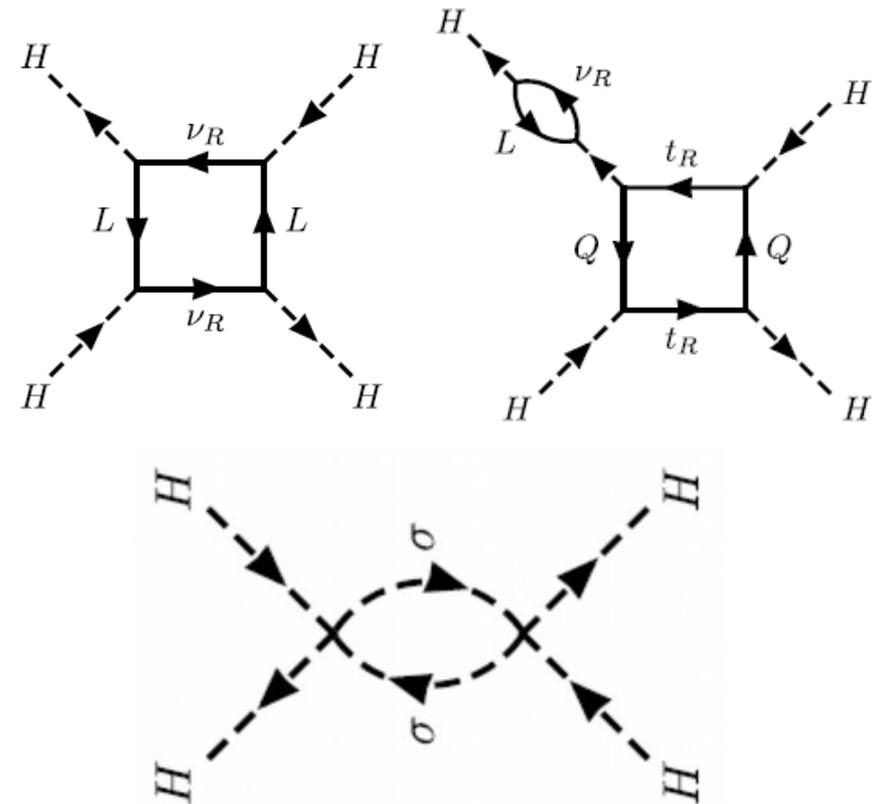
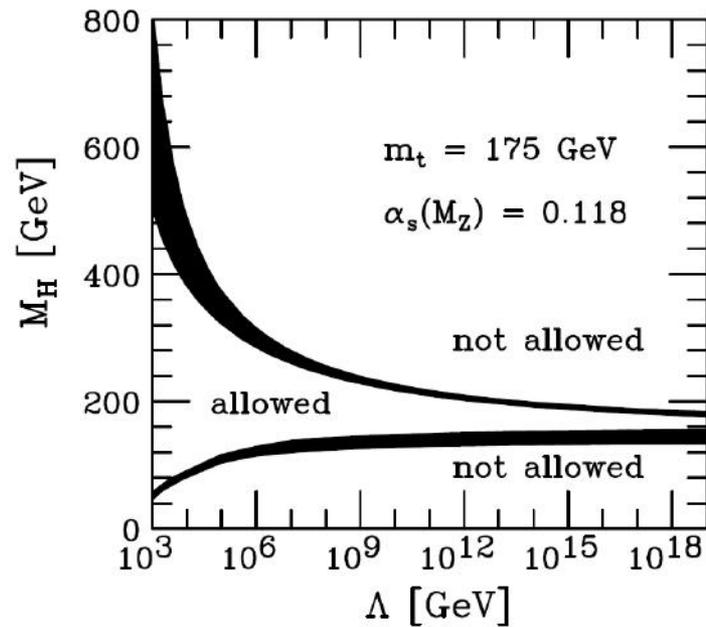


Valle



# SM vacuum and neutrinos

Physics Letters B 756 (2016) 345–349



Valle

**Neutrino mass and invisible Higgs decays at the LHC**Cesar Bonilla,<sup>1,\*</sup> Jorge C. Romão,<sup>2,†</sup> and José W.F. Valle<sup>1,‡</sup>

$$H_i \rightarrow JJ \quad \text{and} \quad H_2 \rightarrow 2H_1 \rightarrow 4J$$

$$\left( \text{when } m_{H_1} < \frac{m_{H_2}}{2} \right).$$

[arXiv:1502.01649](https://arxiv.org/abs/1502.01649)

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

# Neutrino mass and invisible Higgs decays at the LHC

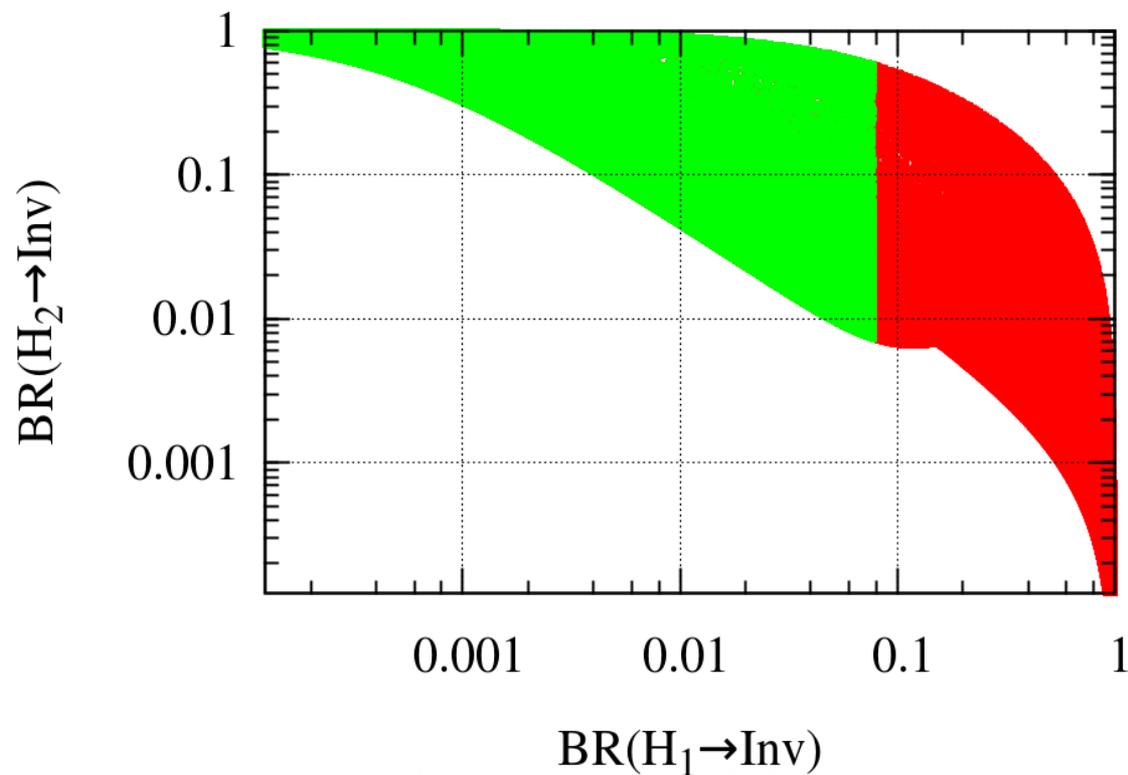
Cesar Bonilla,<sup>1,\*</sup> Jorge C. Romão,<sup>2,†</sup> and José W.F. Valle<sup>1,‡</sup>

$v_\sigma=3$  TeV

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Valle

**Neutrino as  
higgs benchmark**

# Why neutrinos



The road to new physics



# Why neutrinos



The road to new physics



diphoton



# Why neutrinos



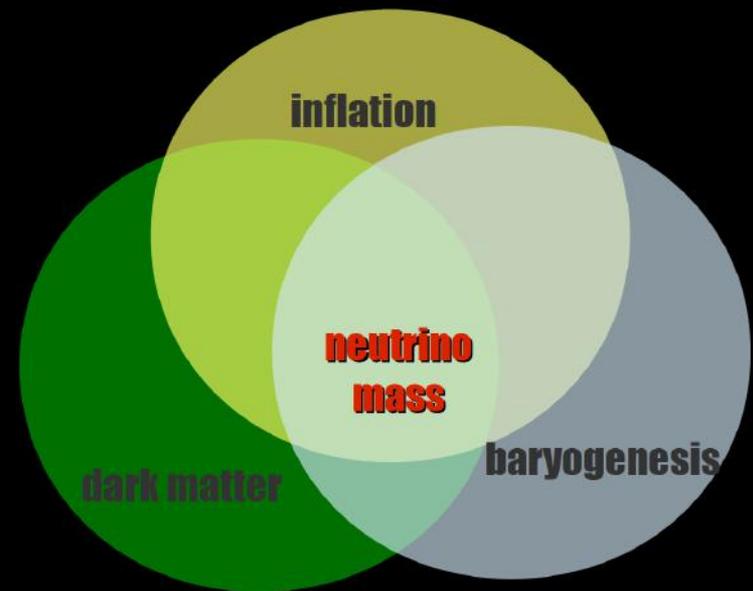
*Basic cosmo & astro probe*

*May explain cosmo puzzles*

*The road to new physics*



diphoton



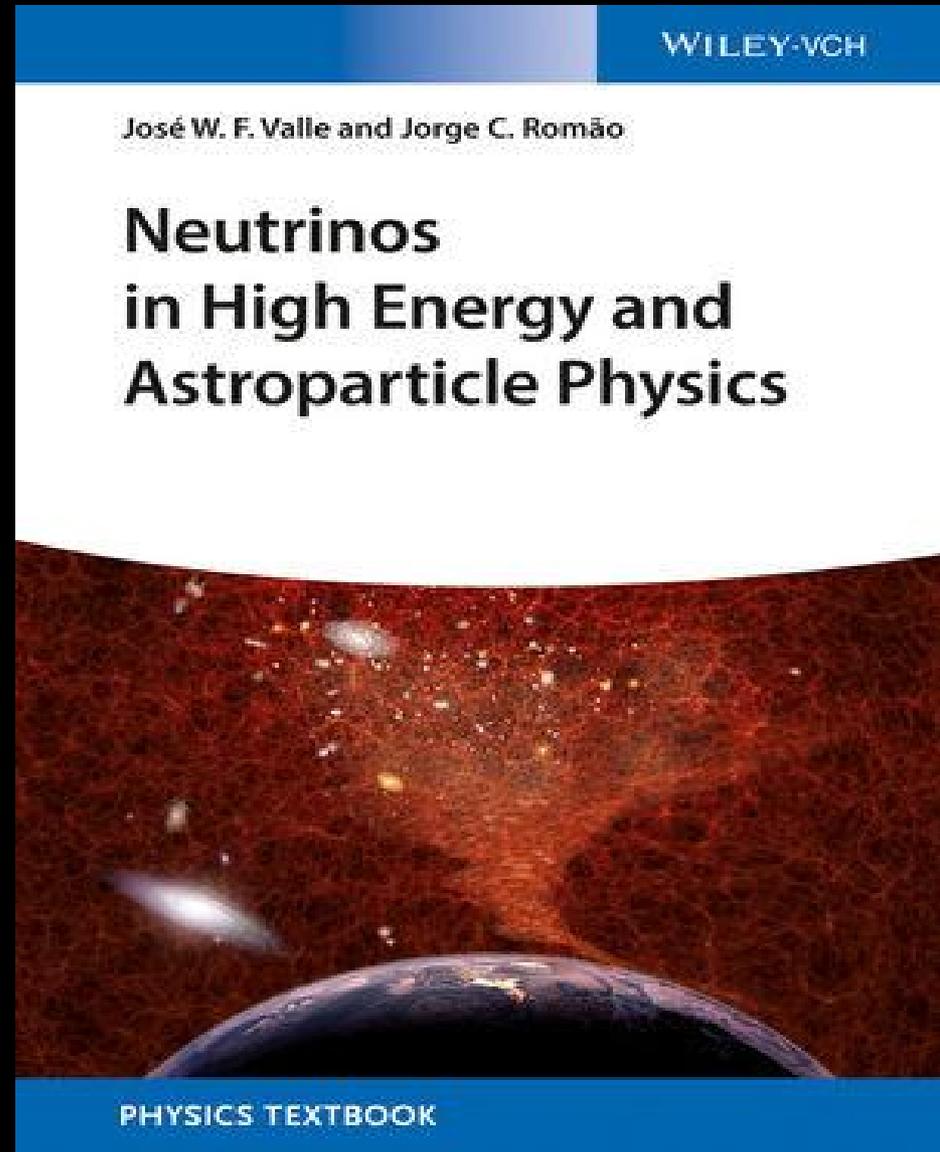
# Thank you

<http://t.co/yUSLiF1cGX>

<fb.me/2ZAD7khZf>

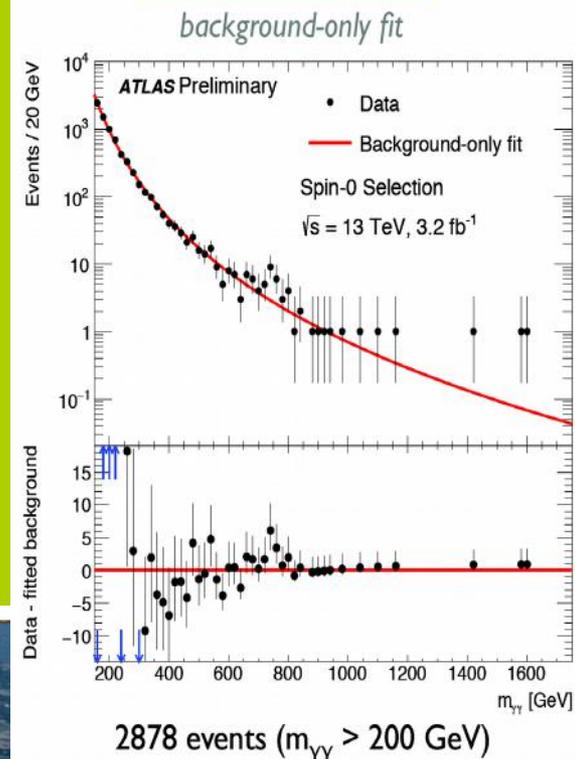
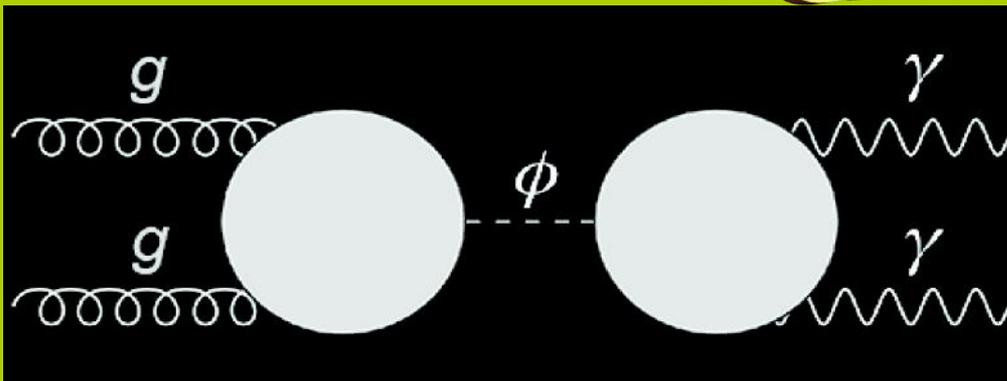
*All you ever  
Wanted to know  
About neutrinos  
As guide to  
New physics*

ISBN: 978-3-527-41197-9  
458 pages  
2015



Backup slides

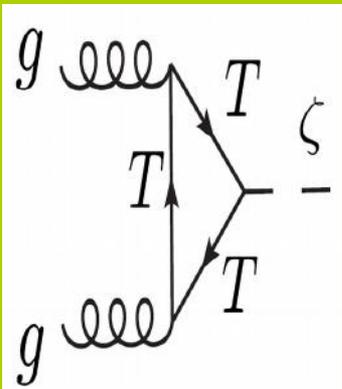
# Diphoton anomaly



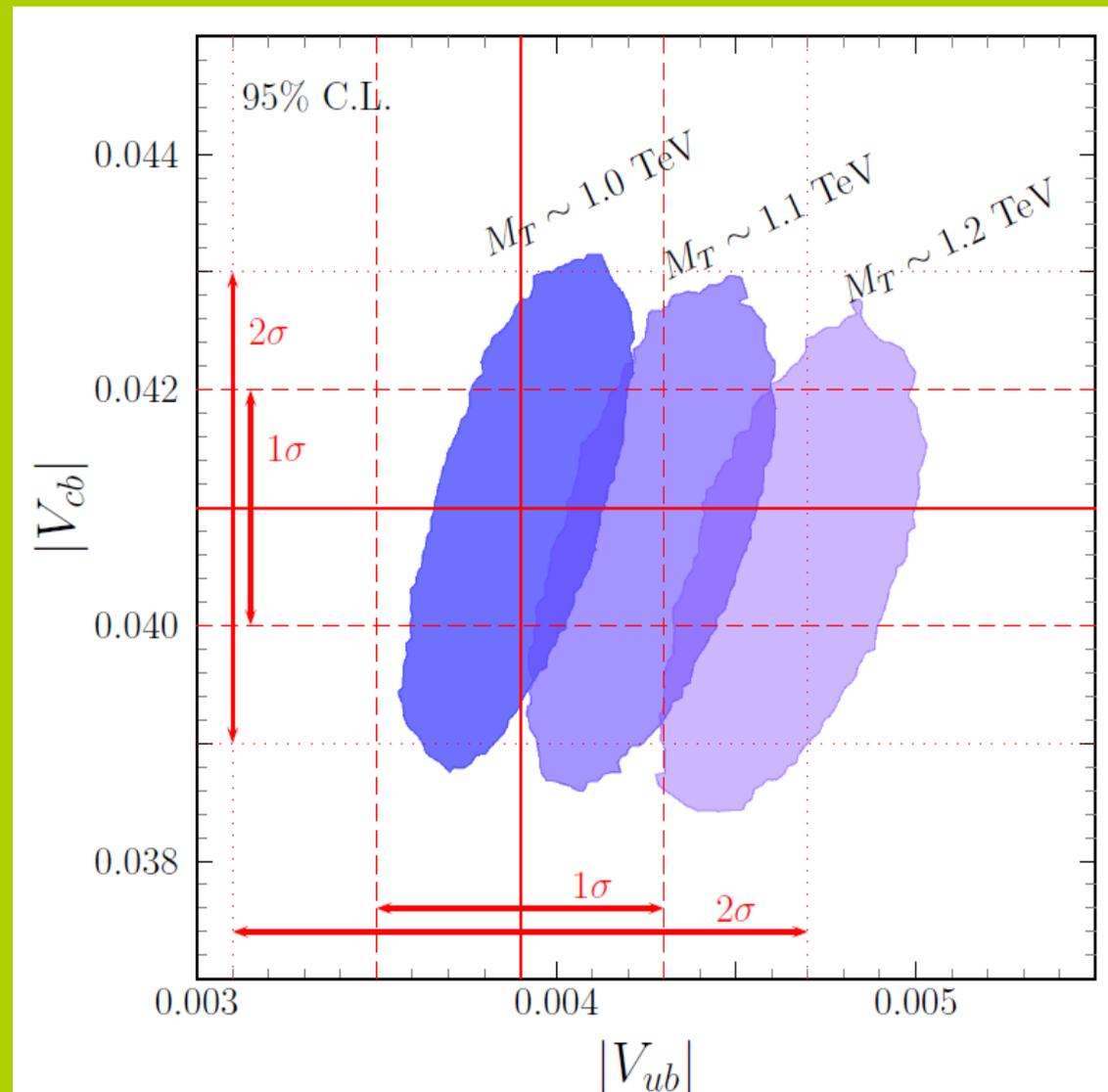
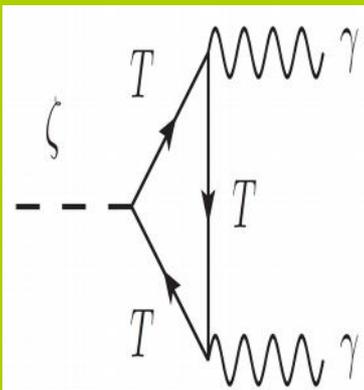
## Large Hadron Collider



# Diphoton anomaly



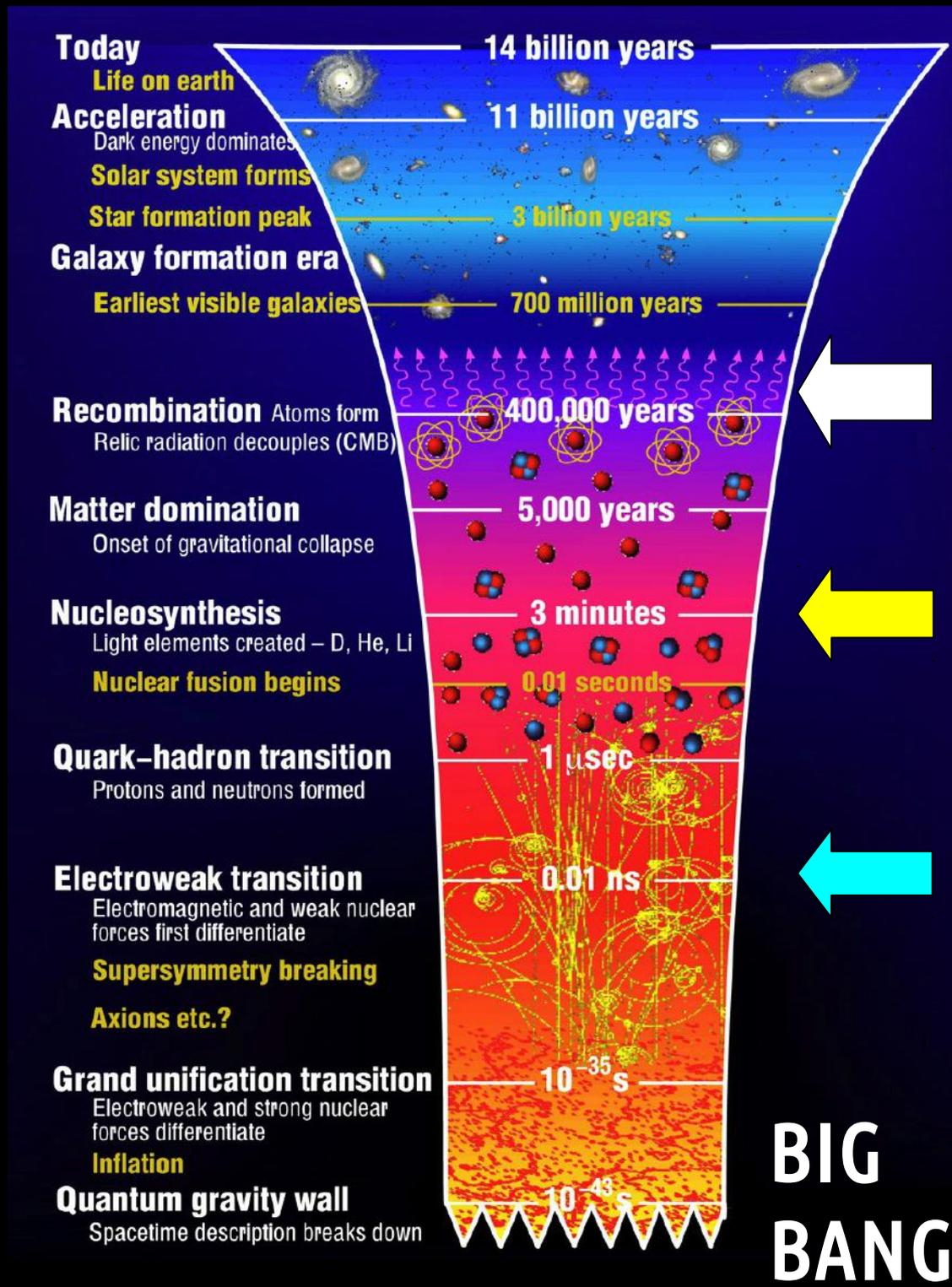
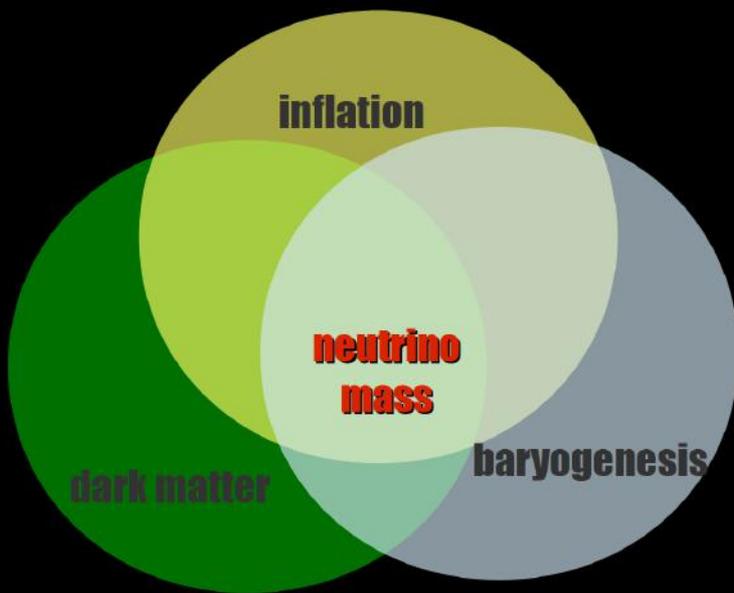
As a flavon



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

DARK MATTER

INFLATON

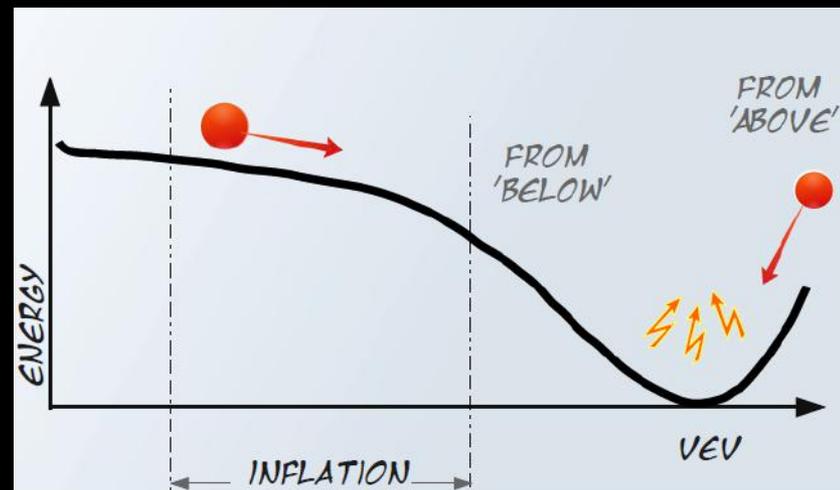
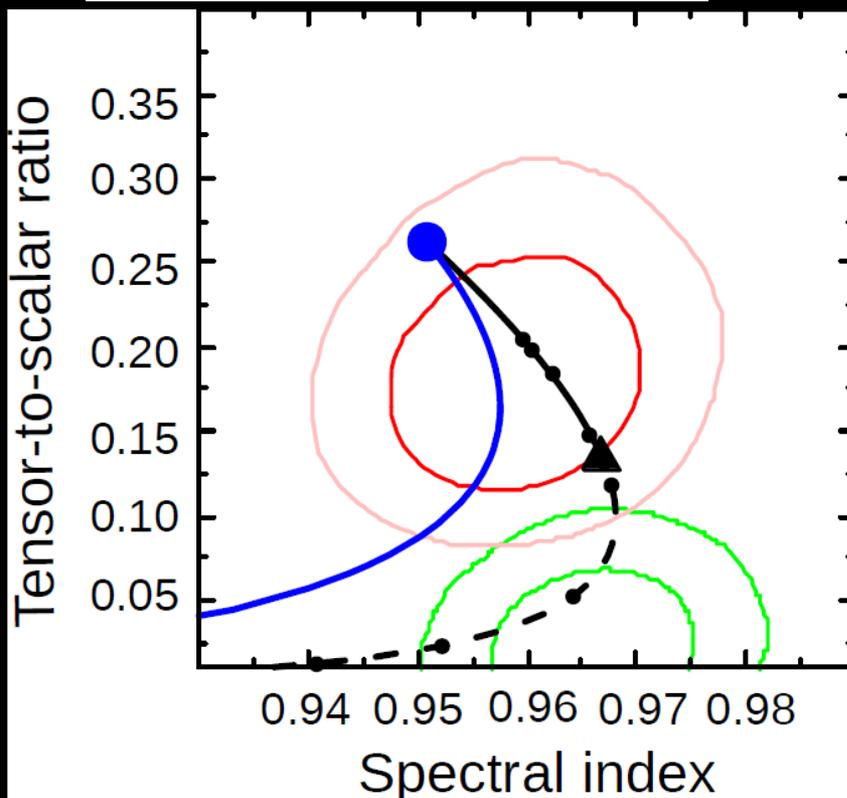
Boucenna et al arXiv:1405.2332

PRD90 (2014) 05502

type-I seesaw **Leptogenesis**

Aristizabal et al arXiv:1405.4706

Quartic versus Higgs Inflation

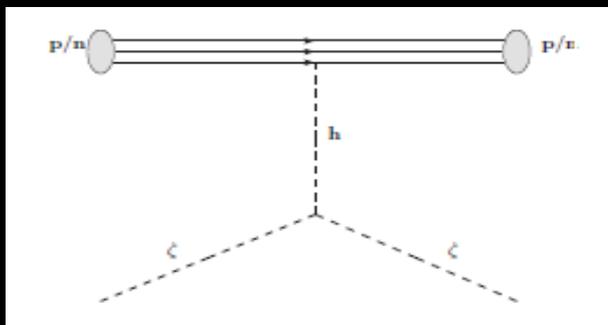
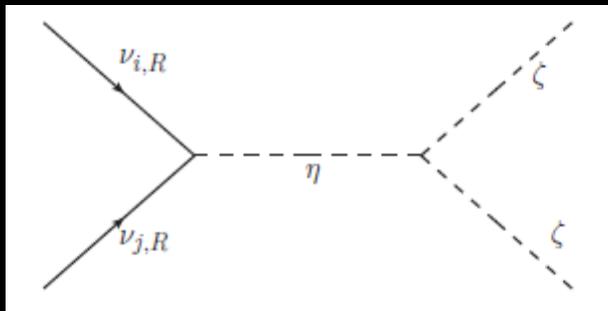
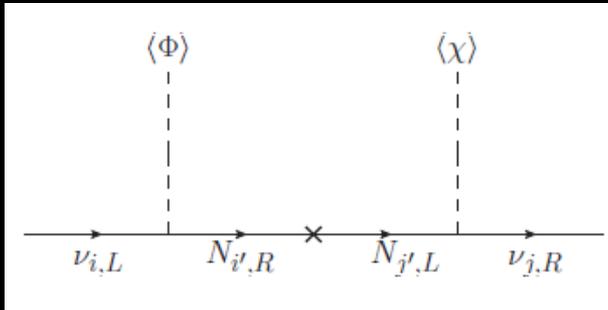


<http://arxiv.org/pdf/1502.00612v1>

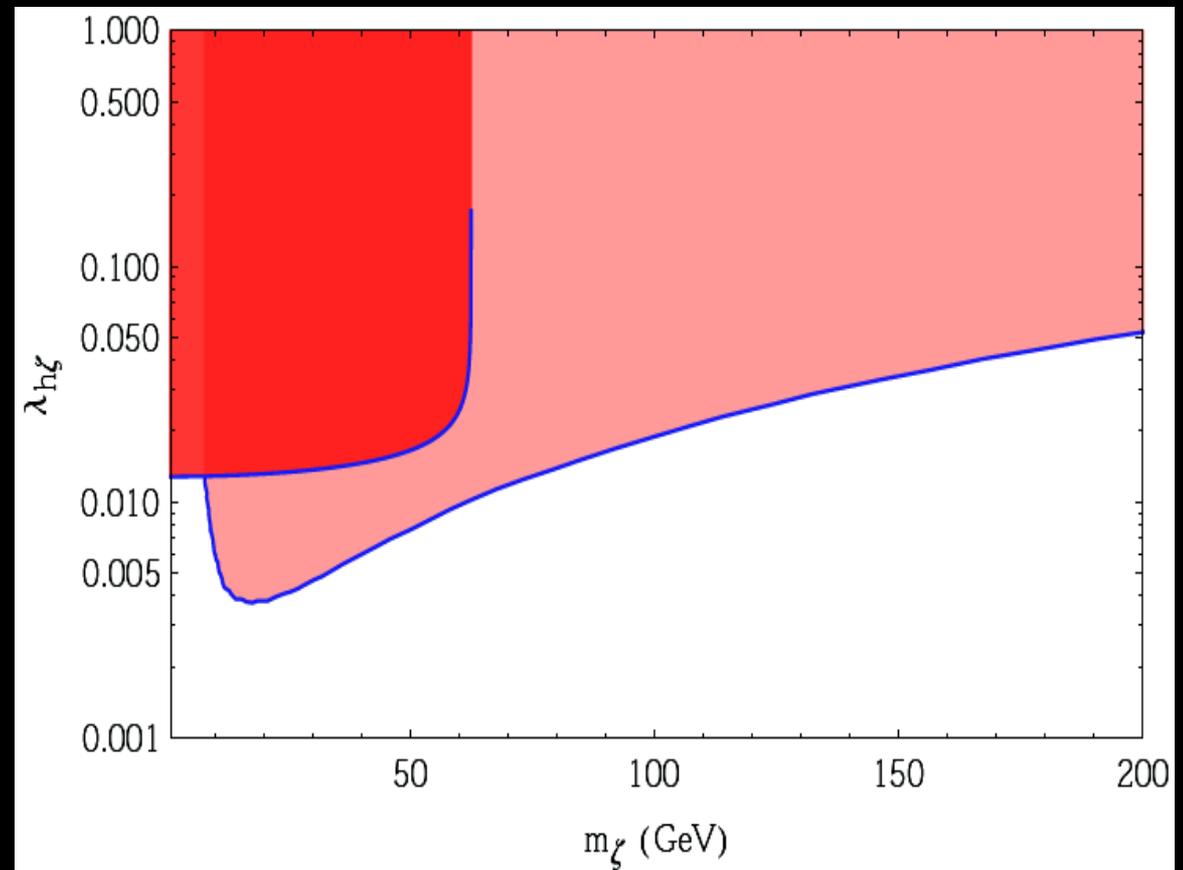
# Dark Matter Stability from Dirac nature of neutrinos

arXiv:1606.04543

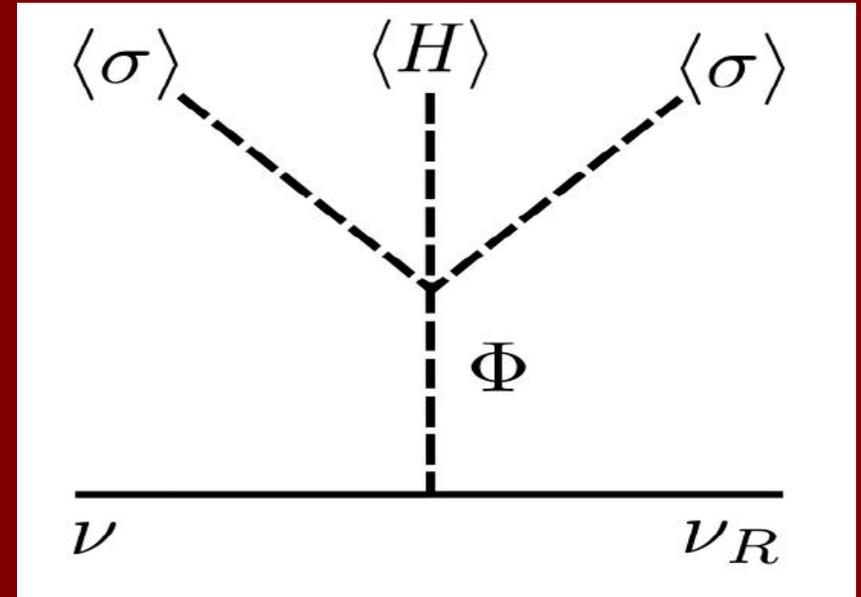
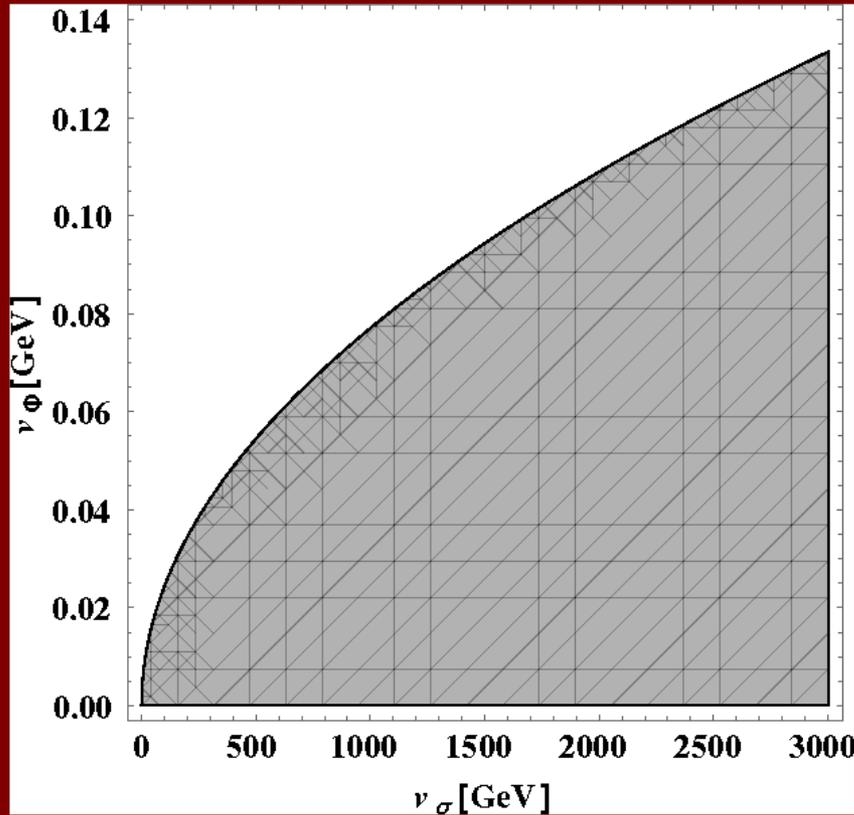
arXiv:1606.06904



## Lepton Quarticity versus Lepton number

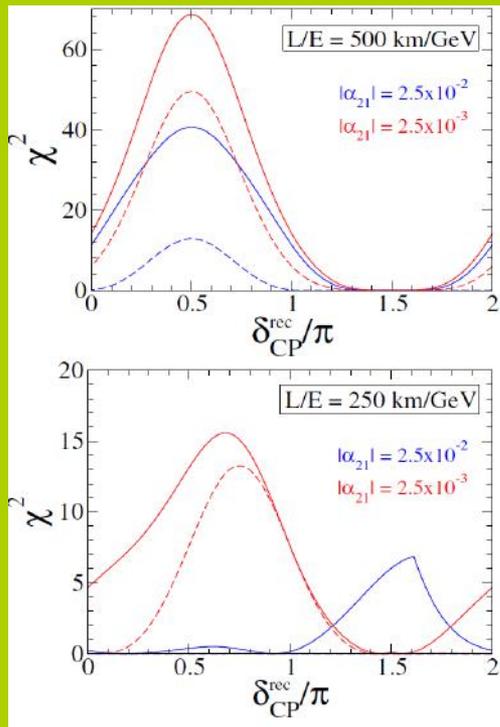


# Diracon type-II seesaw



arXiv:1605.08362

# Non unitary lepton mixing & CP



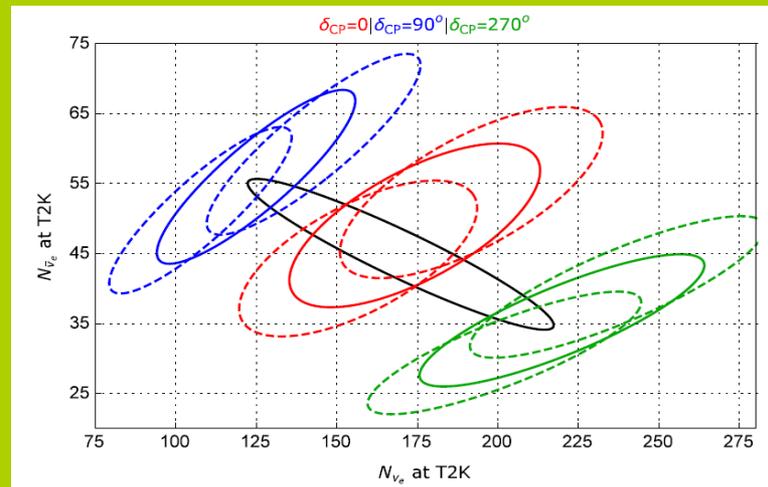
Schechter & JV PRD22 (1980) 2227 & PDG

Rodejohann, JV Phys.Rev. D84 (2011) 073011

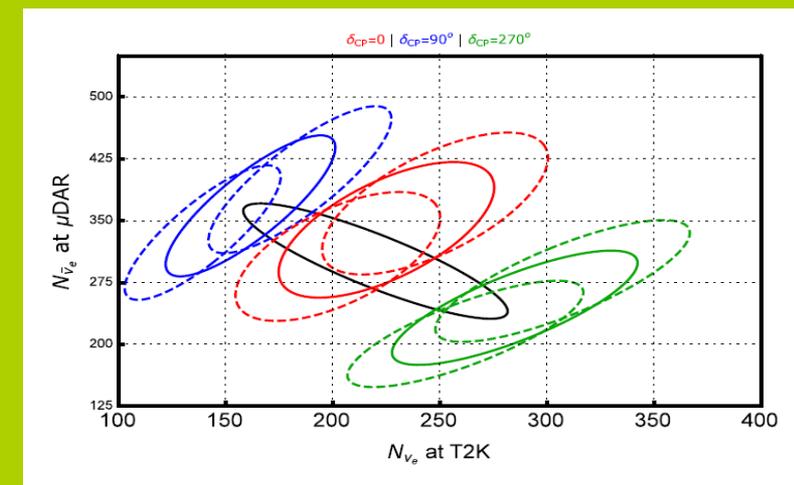
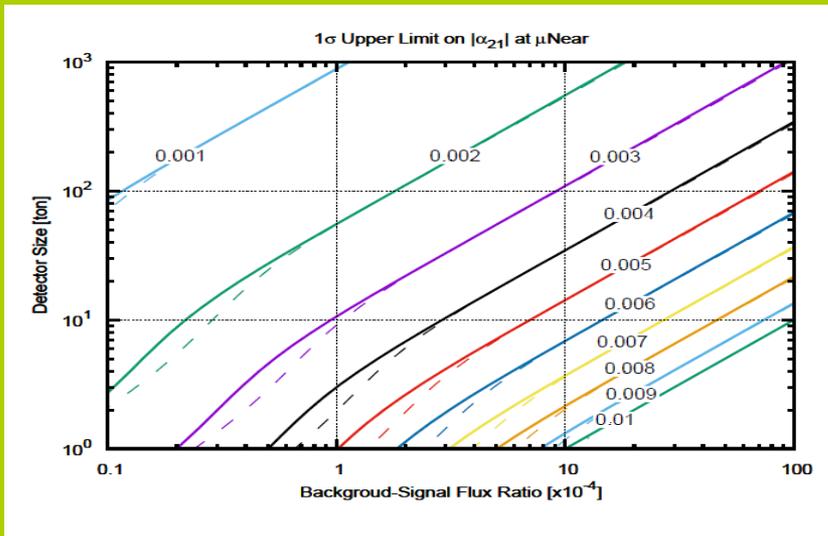
<http://dx.doi.org/10.1103/PhysRevD.92.053009>

arXiv:1604.05690

ArXiv:1605.01670

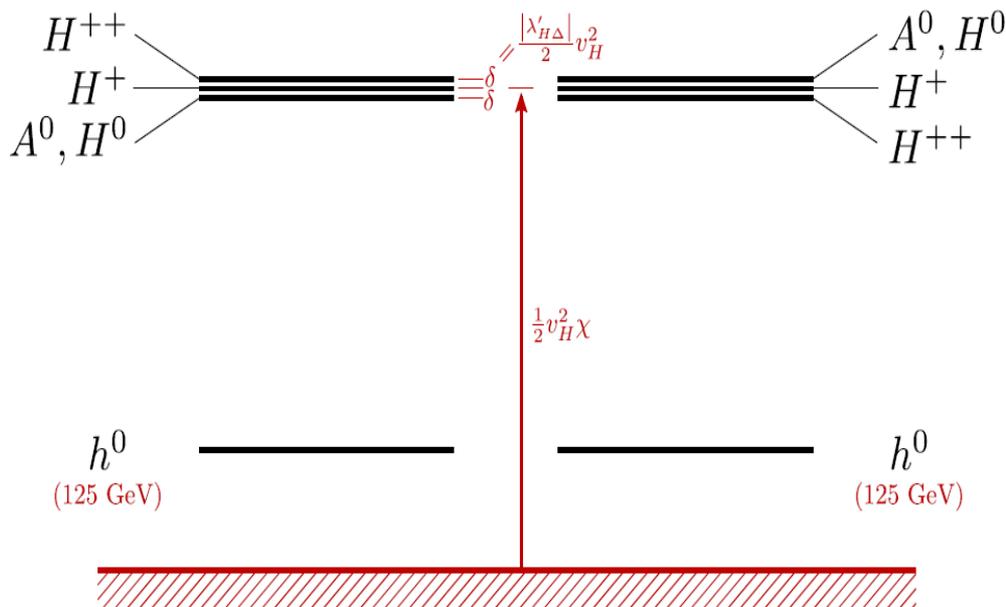
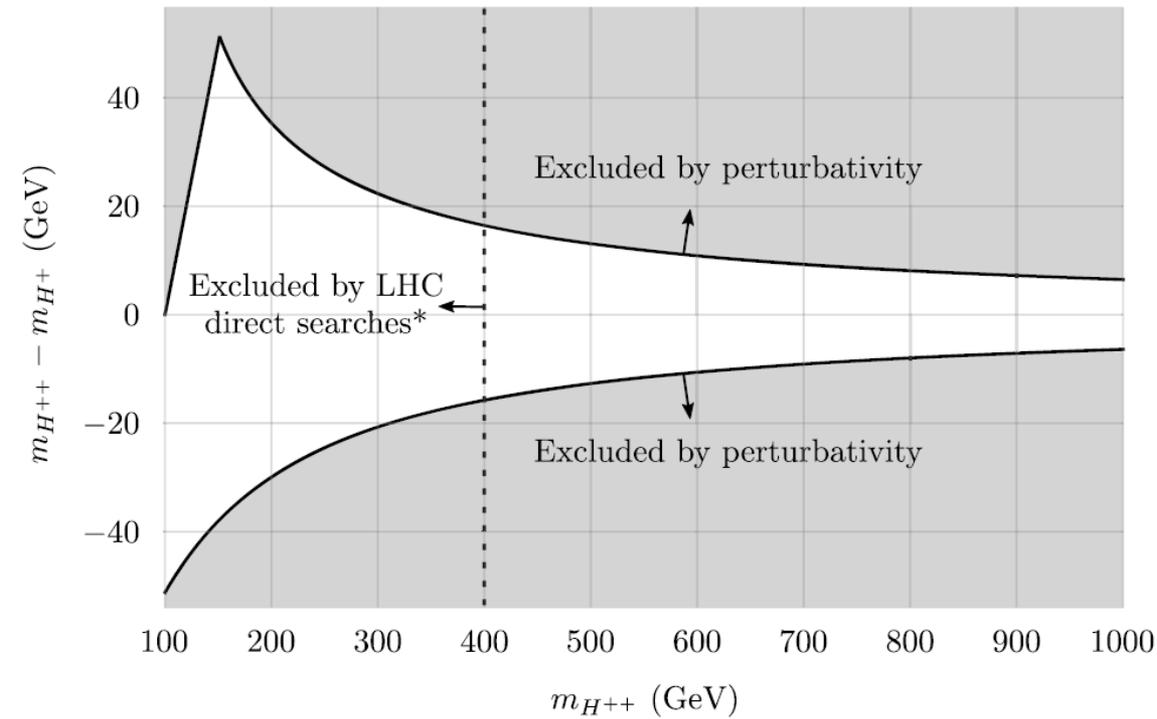


atm



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# Consistency of the triplet seesaw model revisited

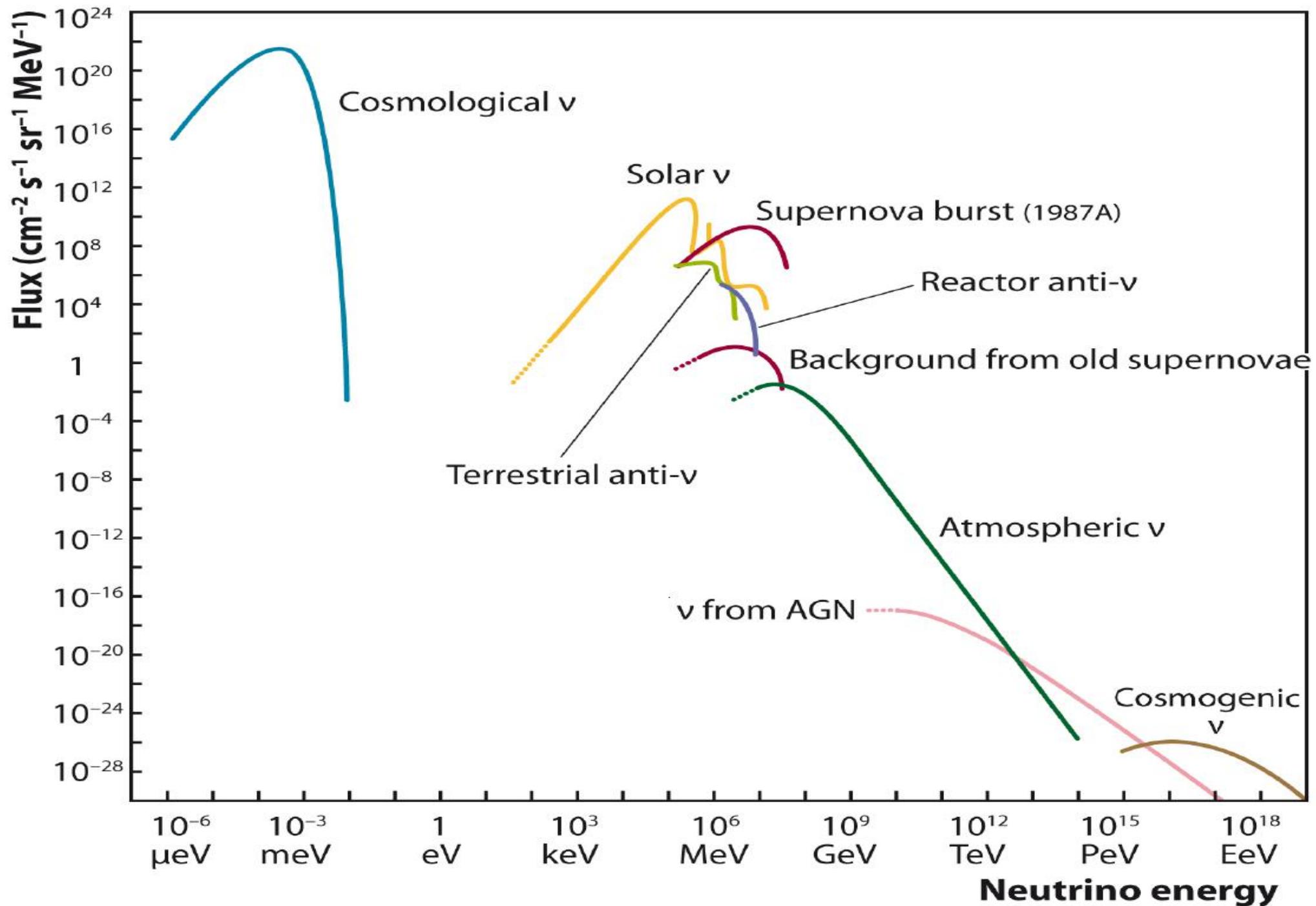


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New J. Phys. 18 (2016) 033033

**Neutrino as  
higgs benchmark**

# neutrino sources



# neutrino cross sections

