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

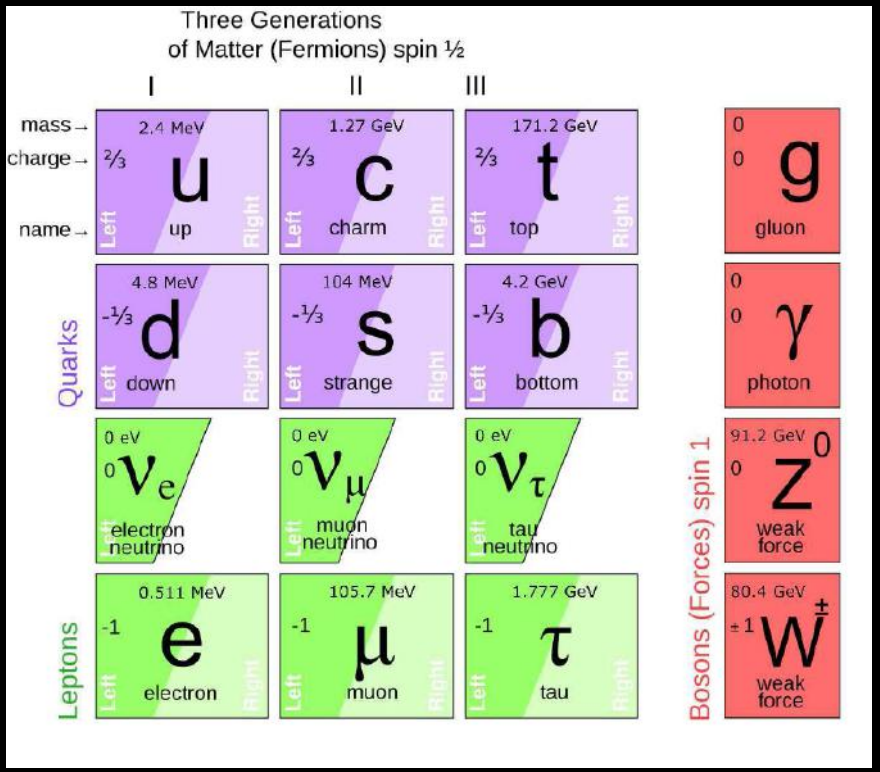
Why neutrinos

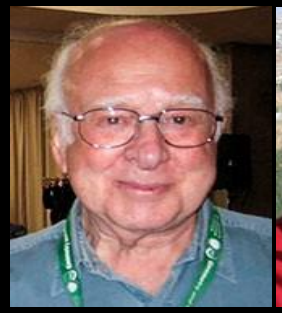
Can not do without neutrinos

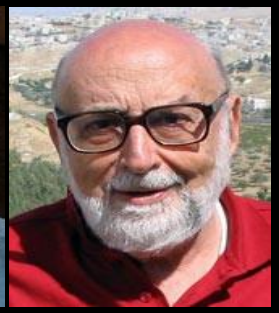
Basic cosmogical and astro probe

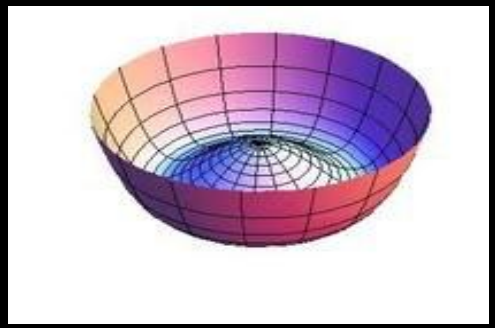
key building block of the Standard Model

Standard model

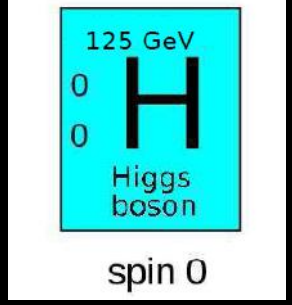


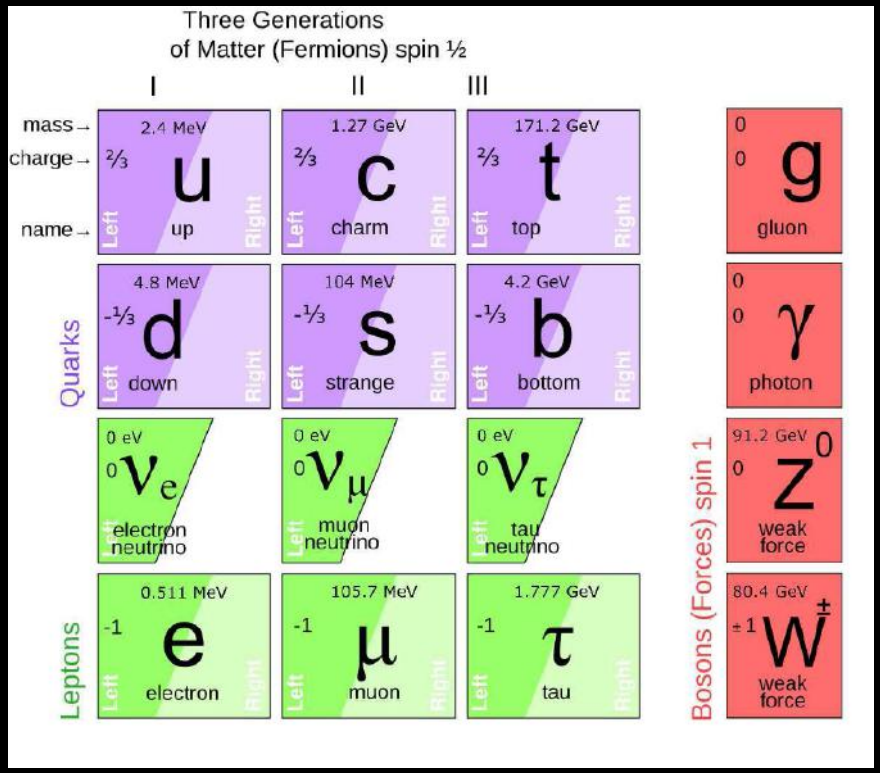


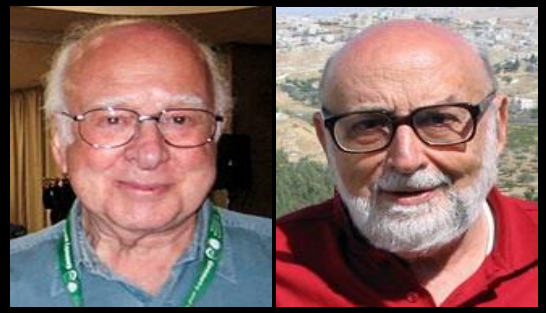


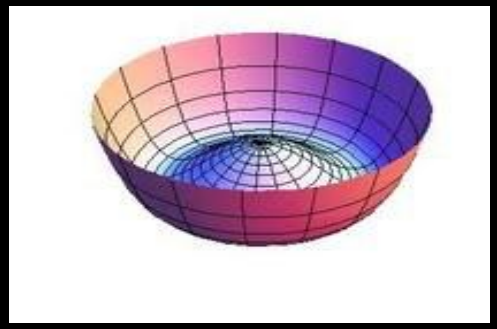


Standard model









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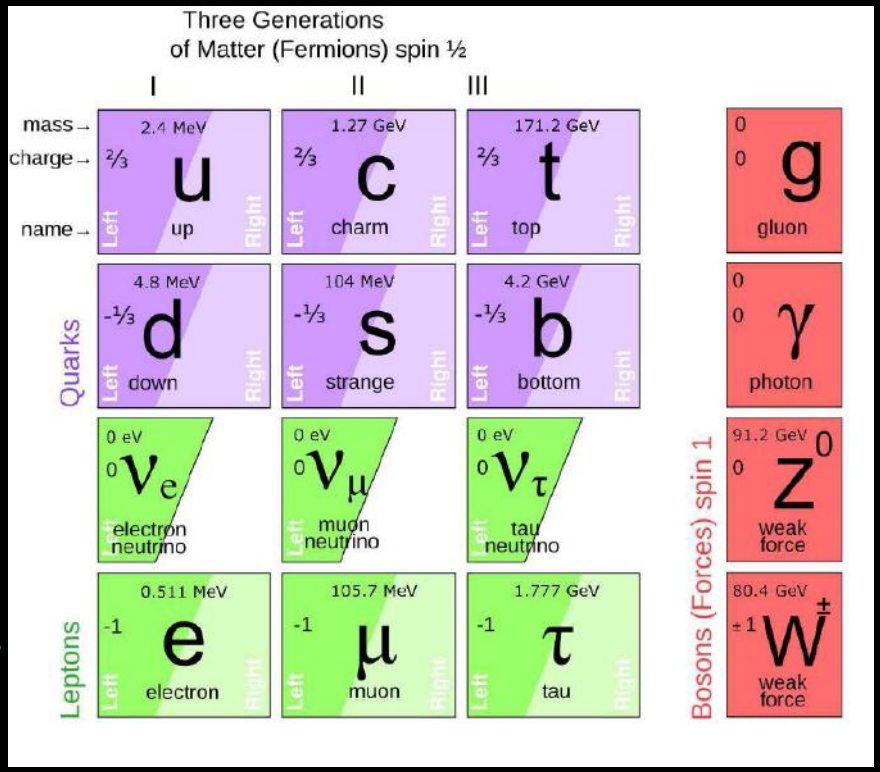
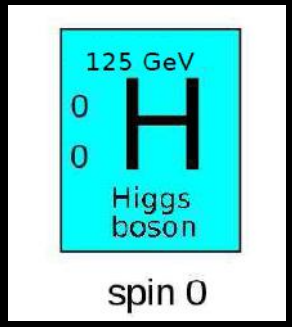
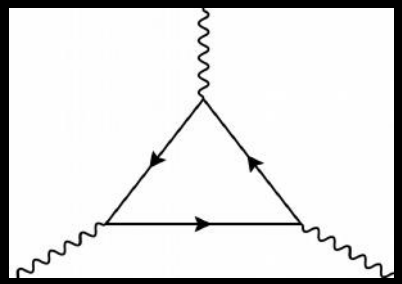




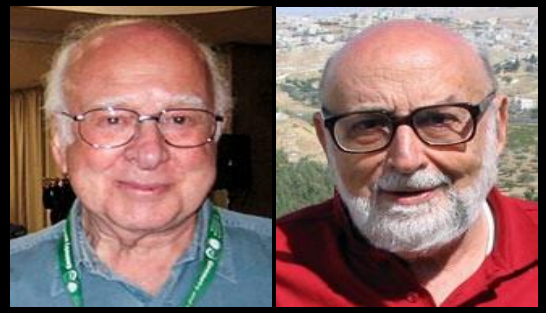
Last brick ? …

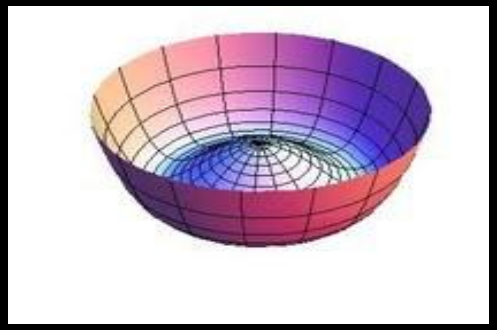
$$-\frac{1}{2} \quad -\frac{1}{2} \quad \frac{1}{6} \quad \frac{1}{6} \quad -1 \quad \frac{2}{3} \quad -\frac{1}{3}$$

anomalies

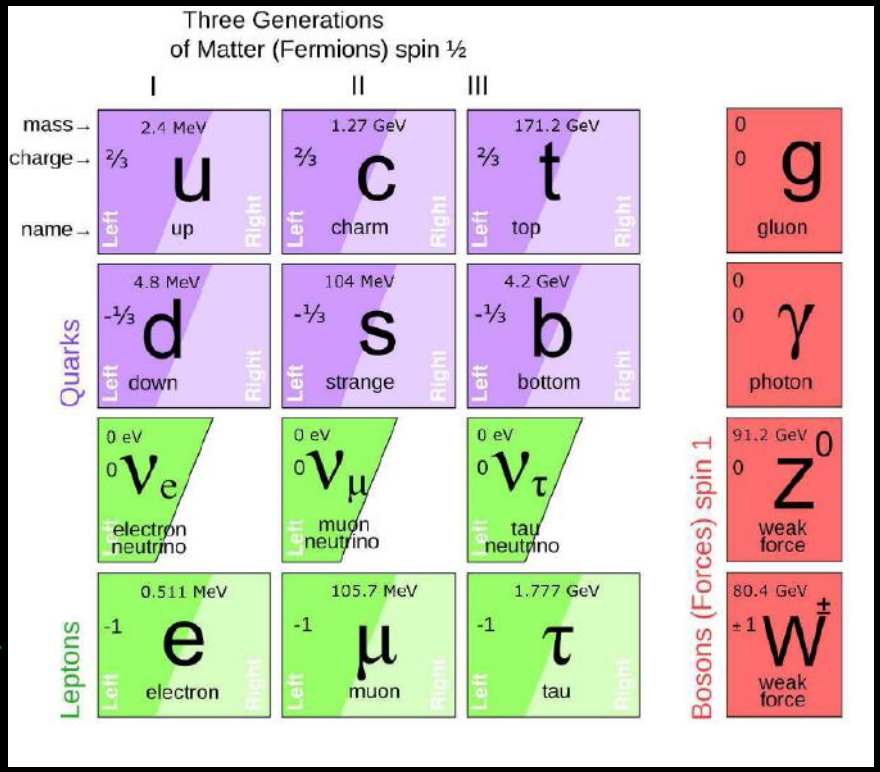


Charge quantization





Standard model



125 GeV
0
0
H
Higgs boson
spin 0

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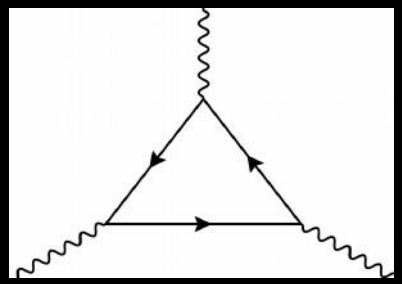
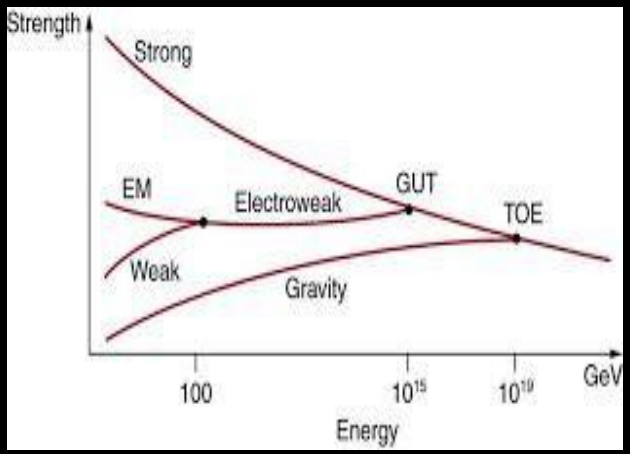
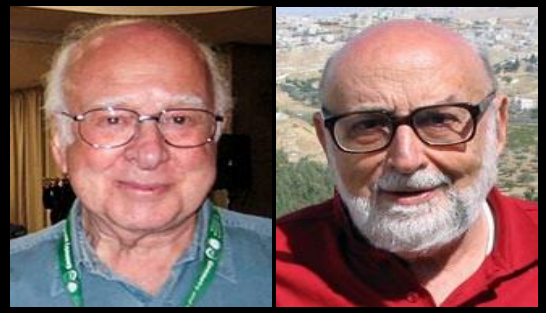
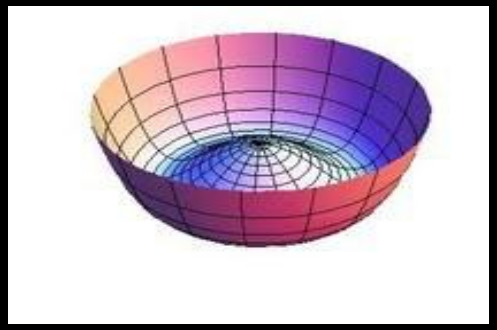


Charge quantization

coupling unification







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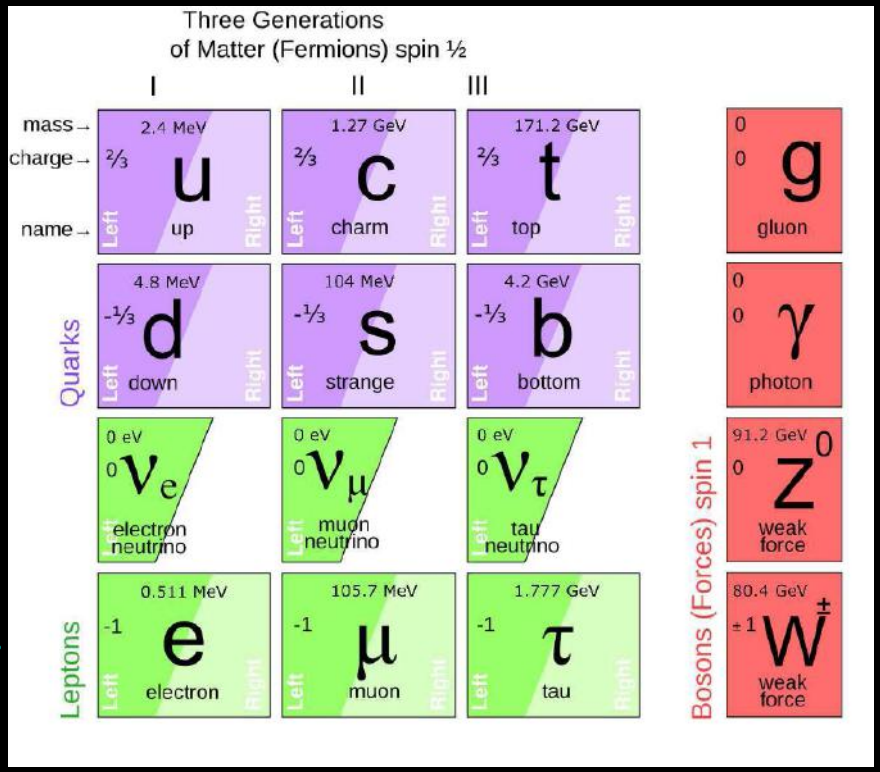

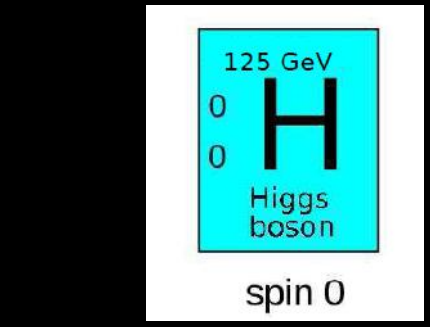

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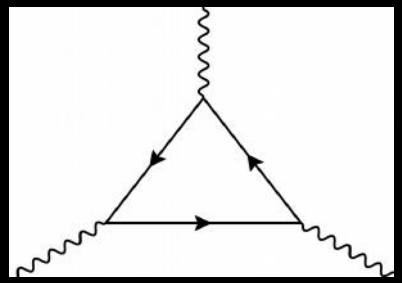

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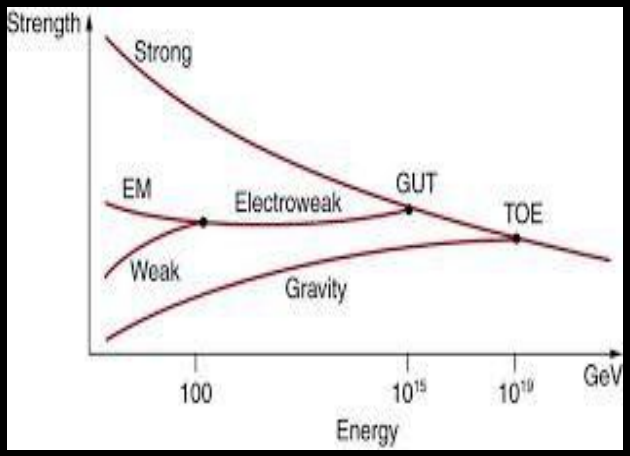
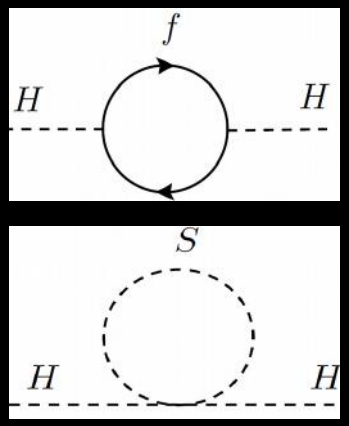


Consistency of SSB

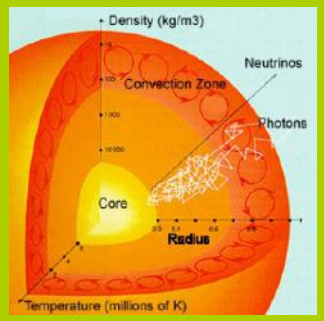


Gravity ...

Why 3 families ...

Neutrino mass

Neutrino oscillations



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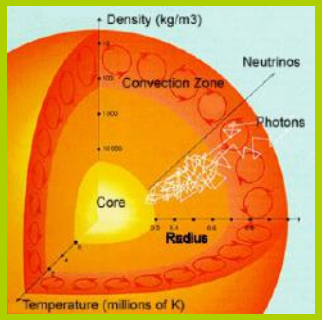
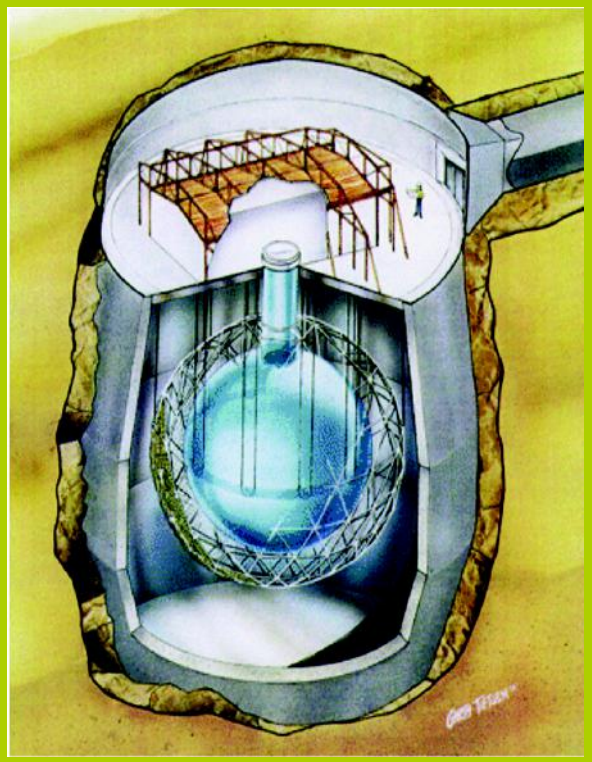
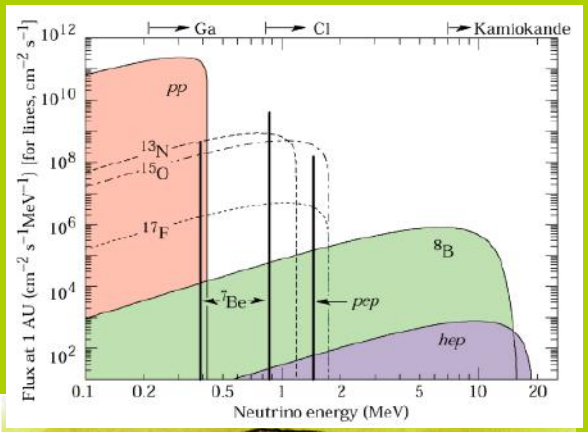
Neutrino oscillations

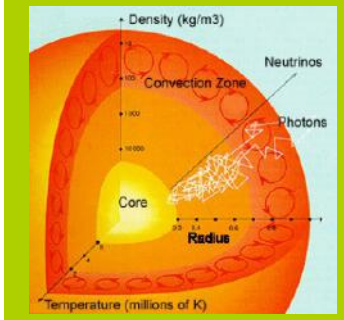


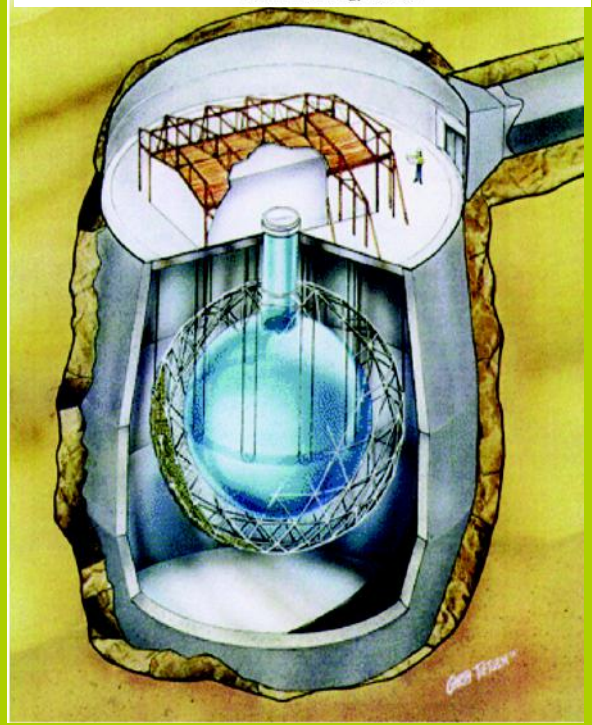


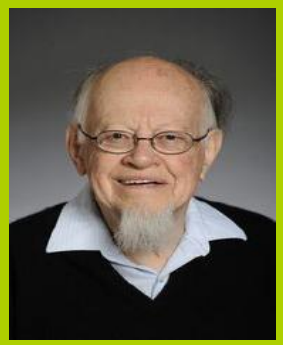
Valle

Neutrino oscillations

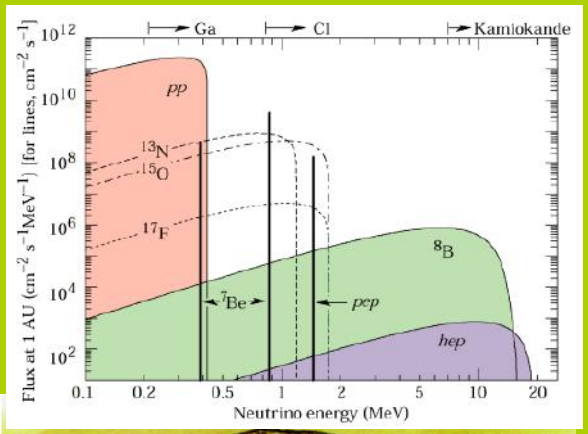


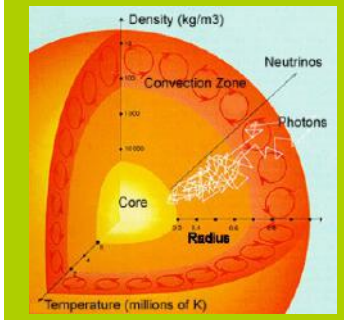


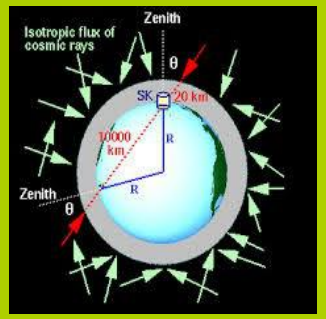


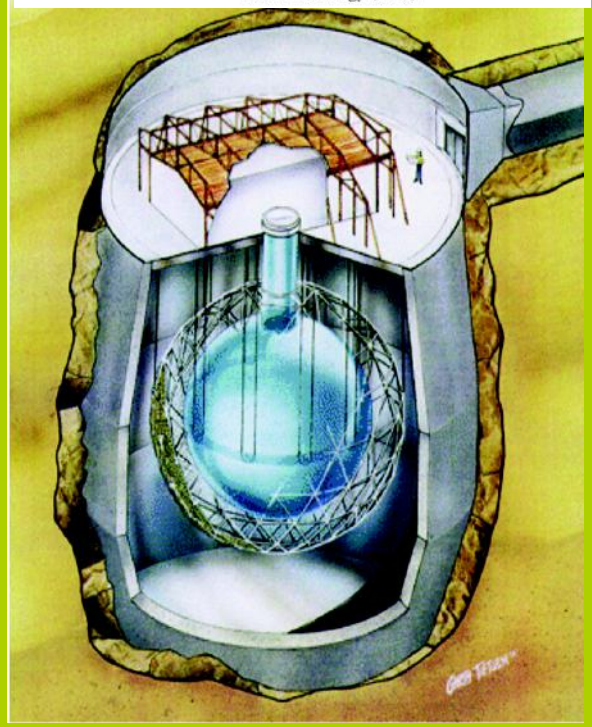


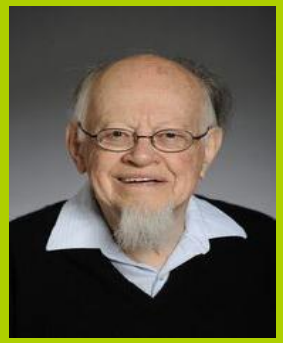
Neutrino oscillations

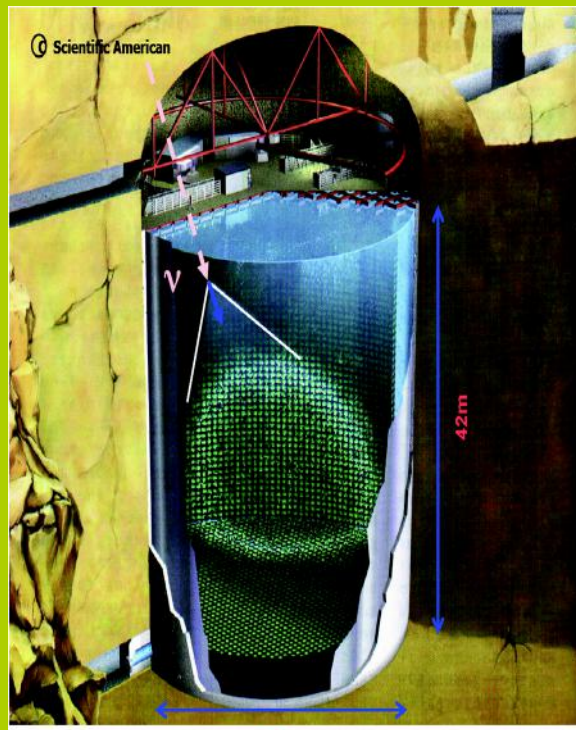




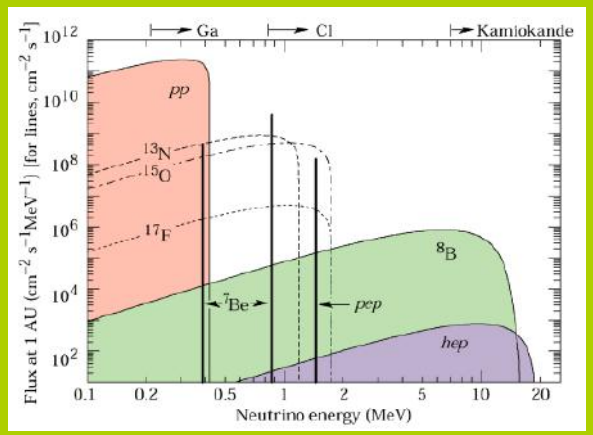


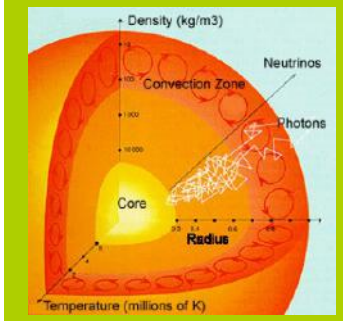


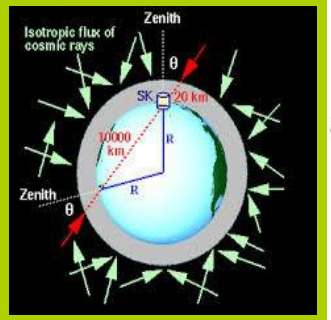


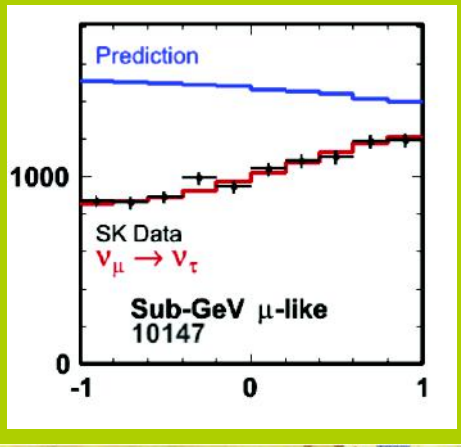


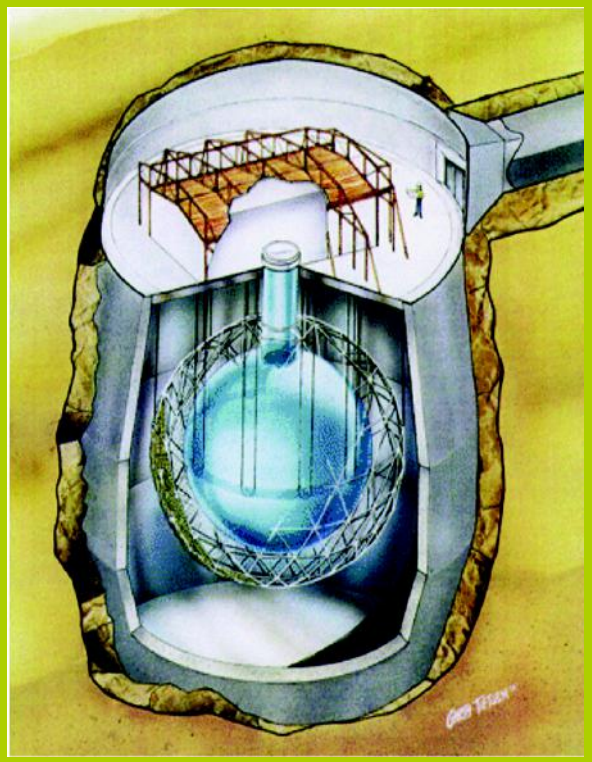
Neutrino oscillations

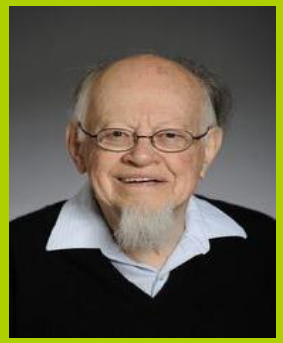


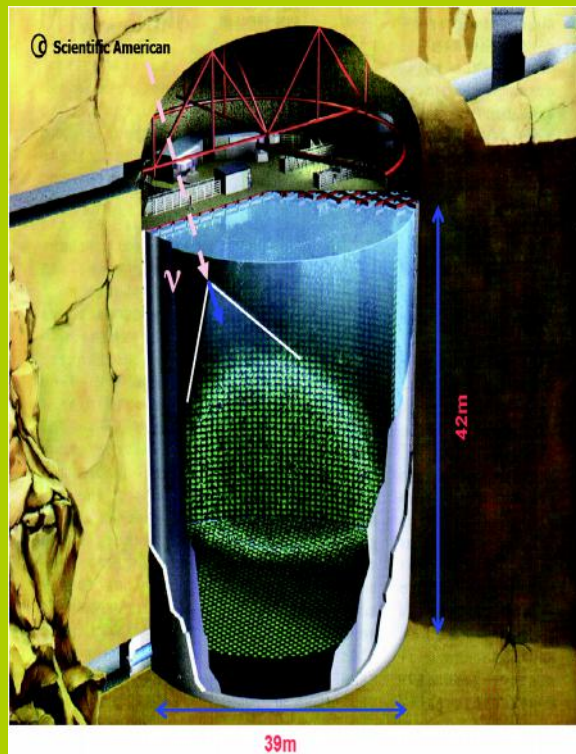






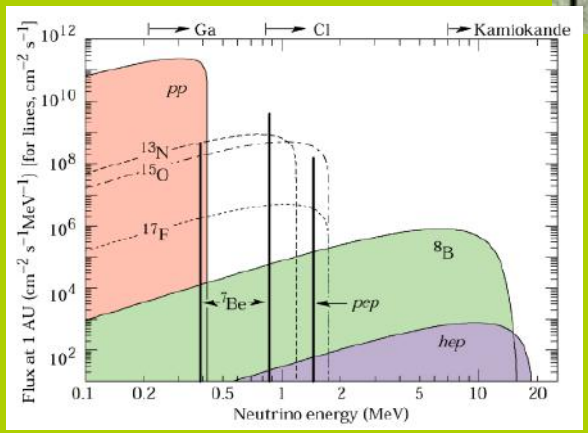


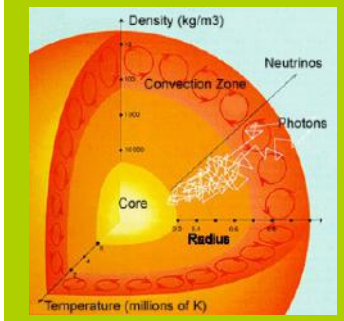


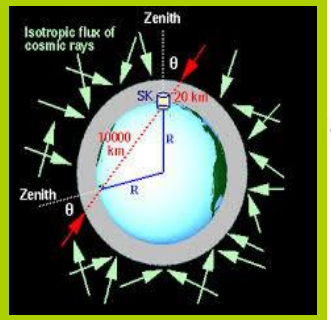


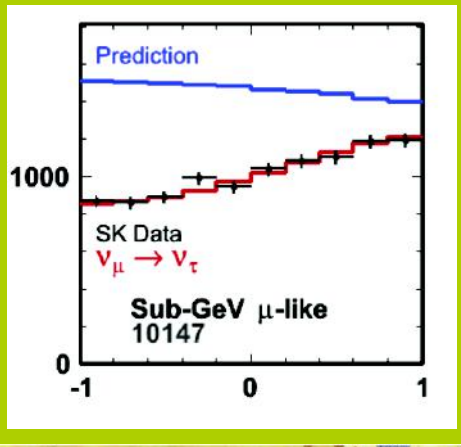
Neutrino oscillations

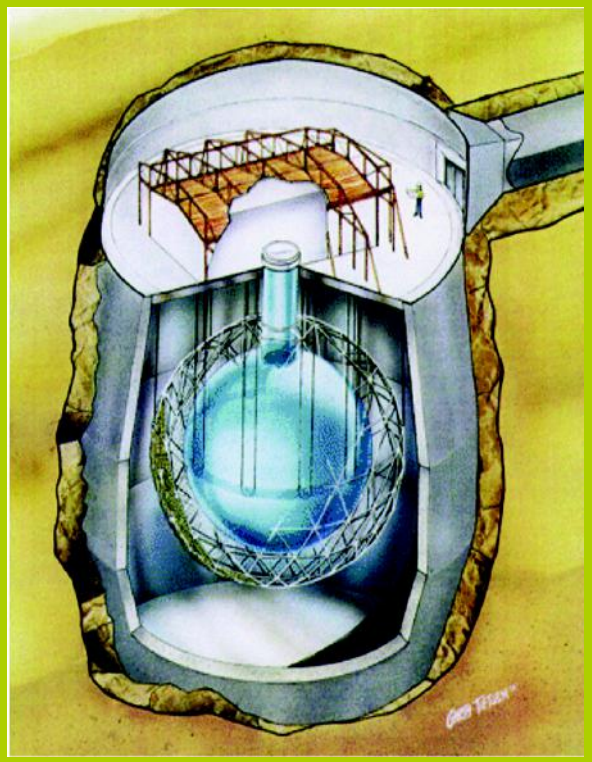
The Nobel Prize in Physics 2015

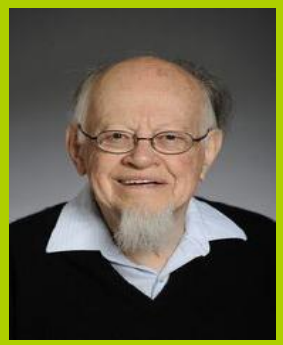


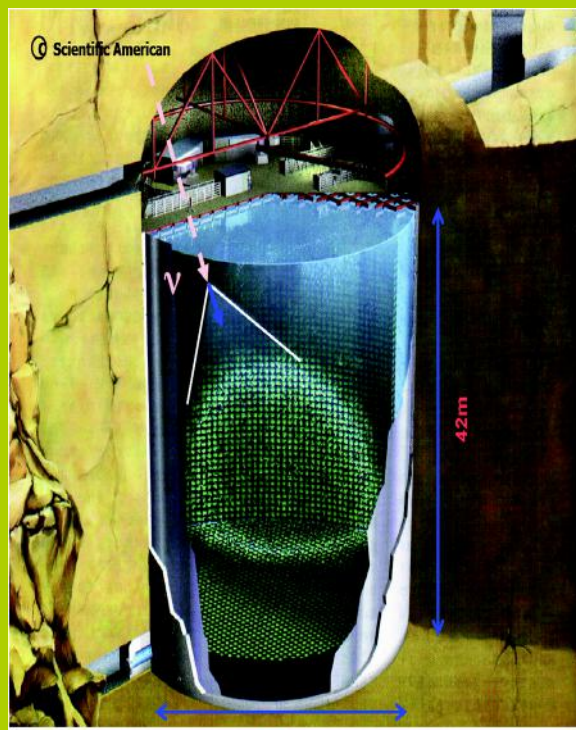


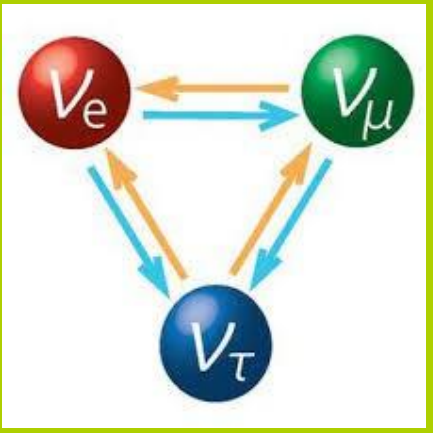




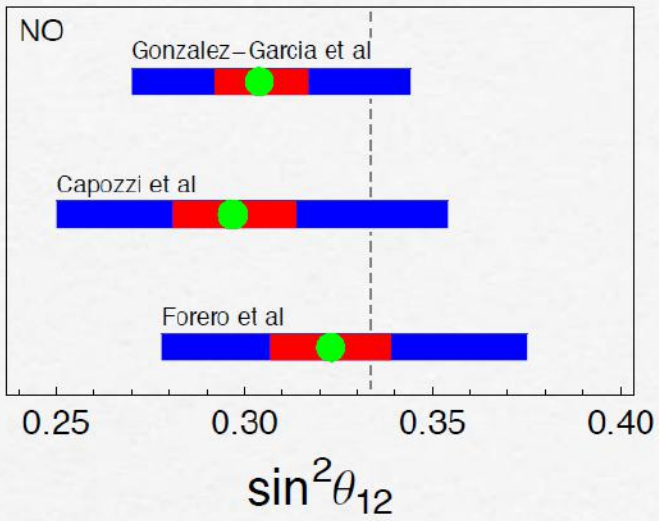


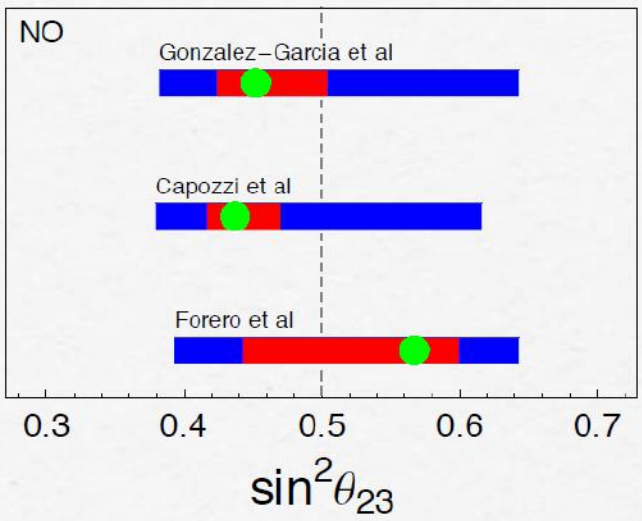


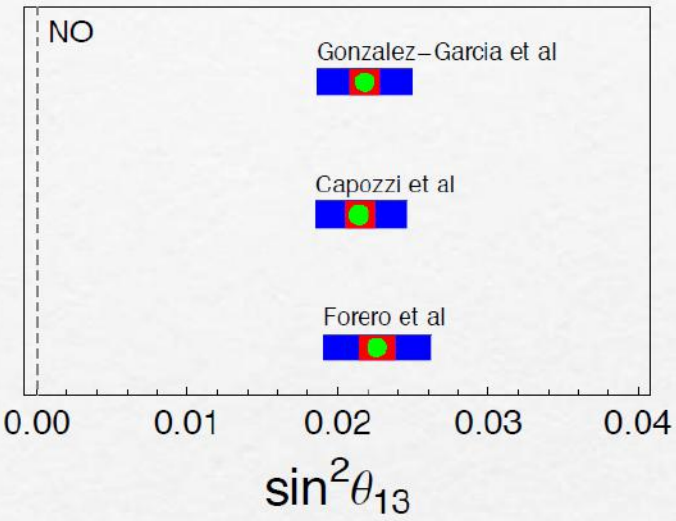


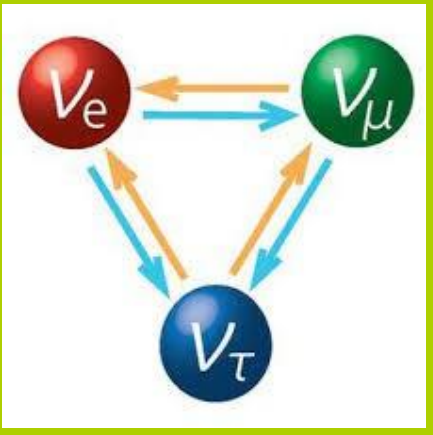


Oscillation parameters

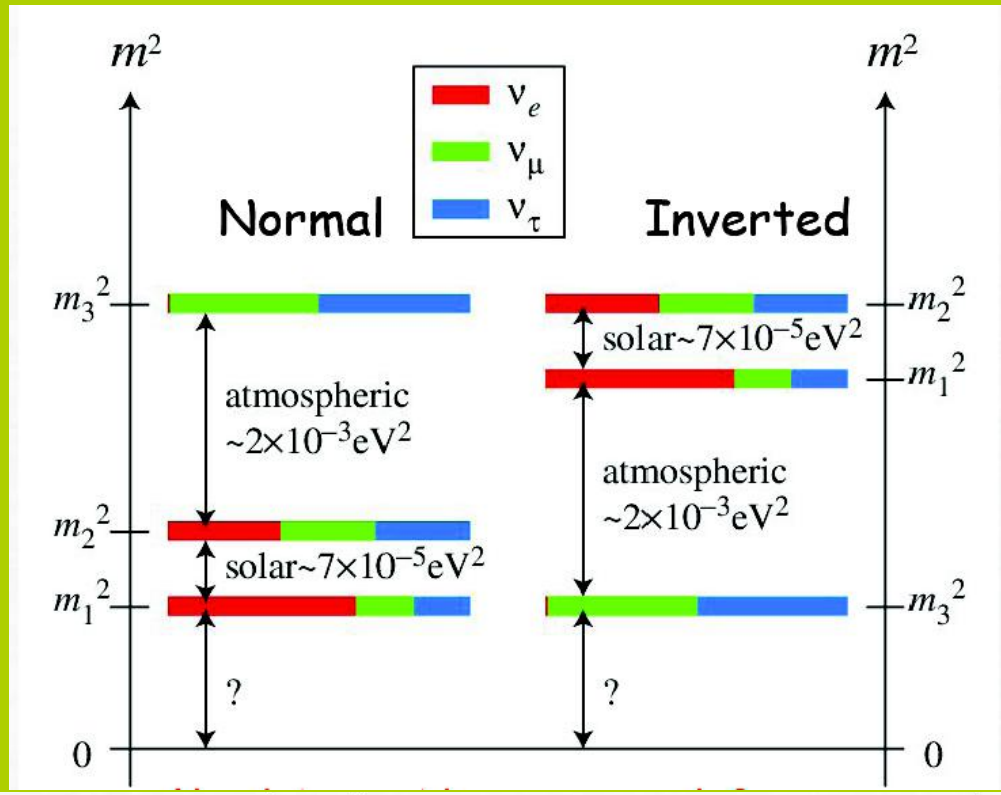


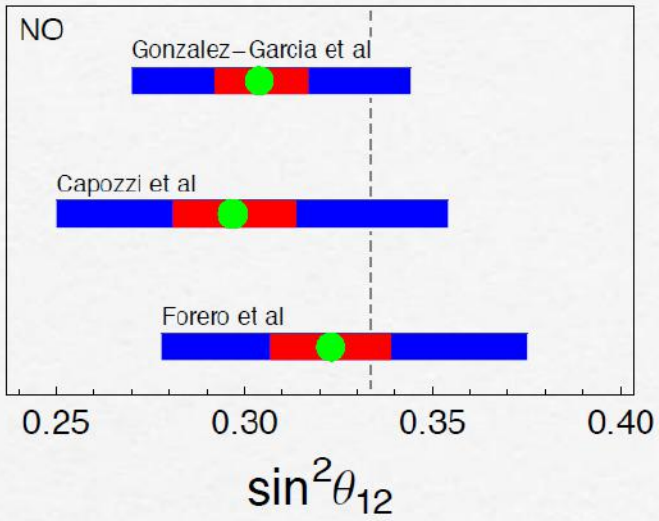


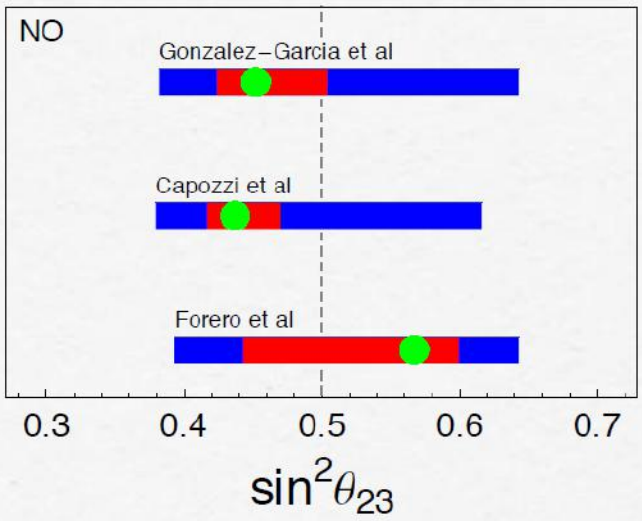


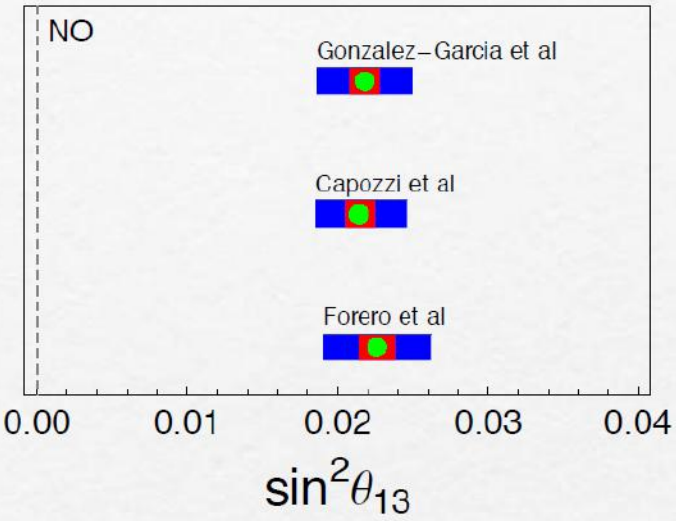


Oscillation parameters





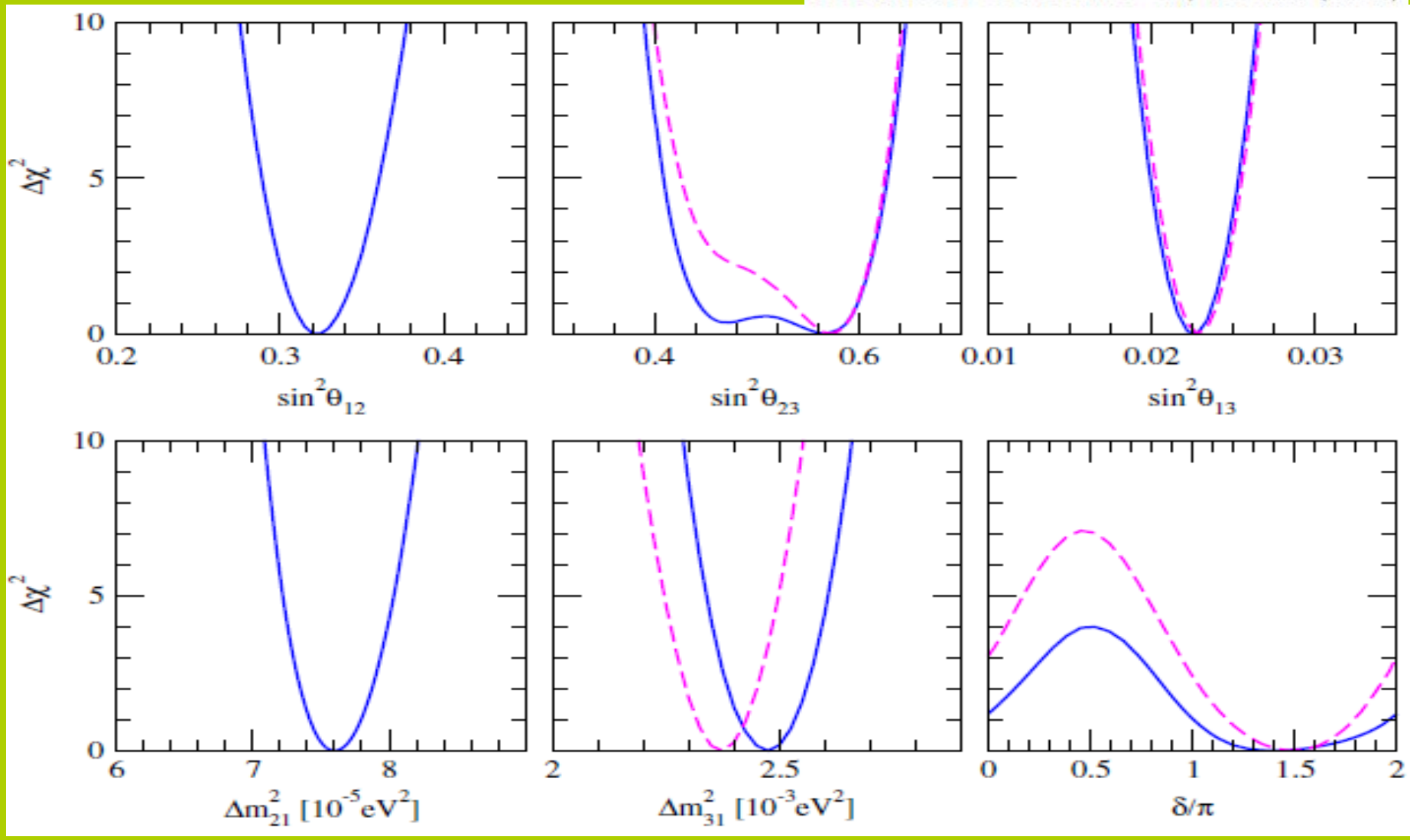




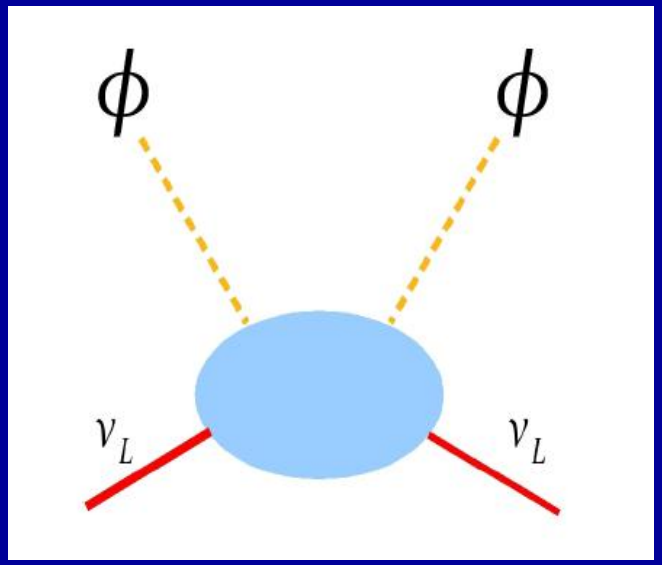
Oscillation parameters

Precision era starts

PHYSICAL REVIEW D 90, 093006 (2014)



The origin of neutrino mass

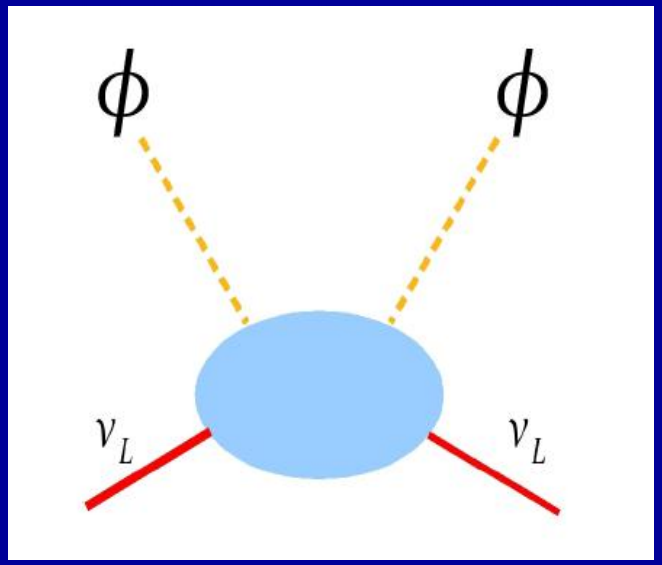


MECHANISM

SCALE

FLAVOR STRUCTURE

The origin of neutrino mass

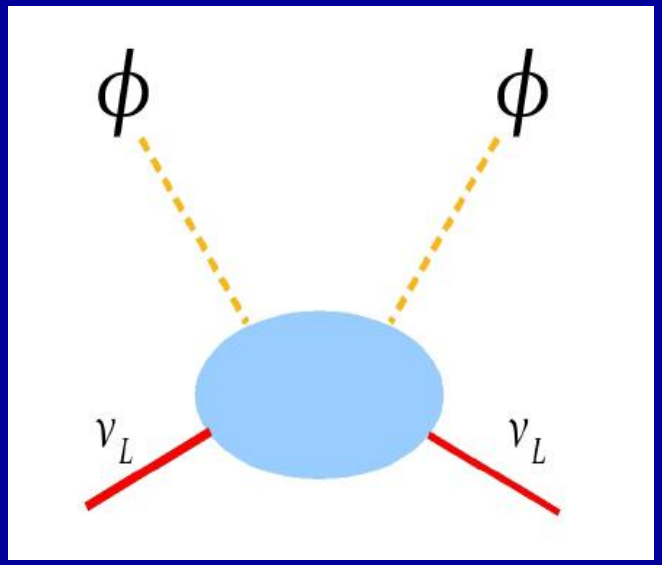


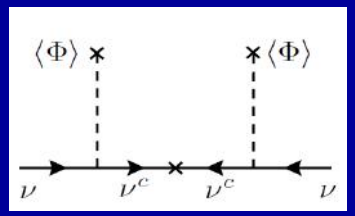
Seesaw

$$v_3 v_1 \sim v_2{}^2$$

- MECHANISM
- SCALE
- FLAVOR STRUCTURE

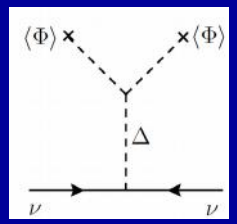
The origin of neutrino mass





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

FLAVOR STRUCTURE

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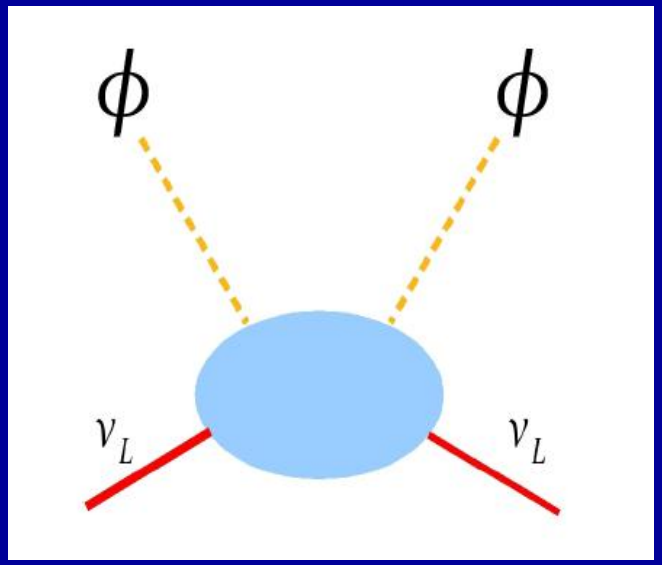

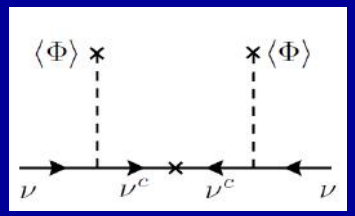

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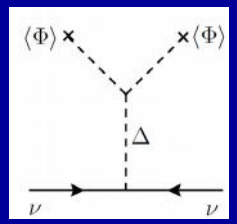

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Schechter-Valle 80/82

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MECHANISM

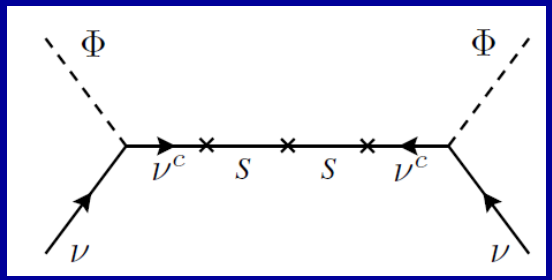
SCALE

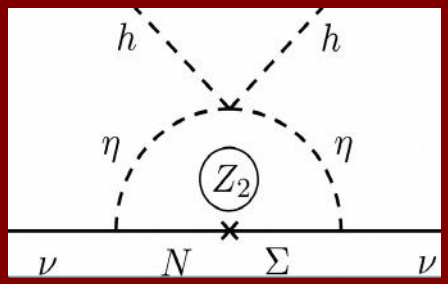
FLAVOR STRUCTURE

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

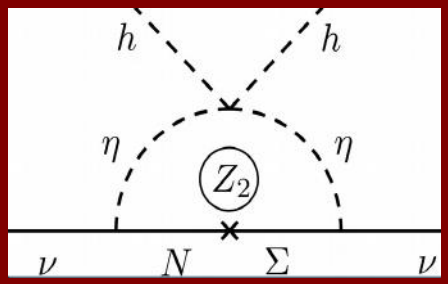




Radiative neutrino mass

many low-scale neutrino mass schemes ...

arXiv:1404.3751



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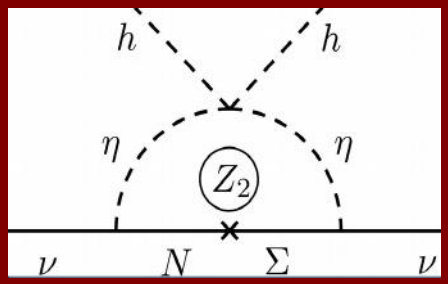
331 electroweak theory # generations = # colours

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



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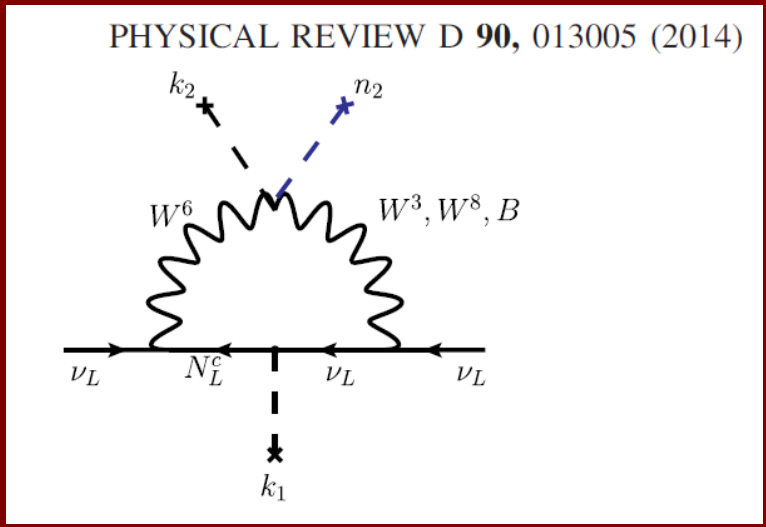
Gauge vs Higgs



BOUCENNA, MORISI, AND VALLE

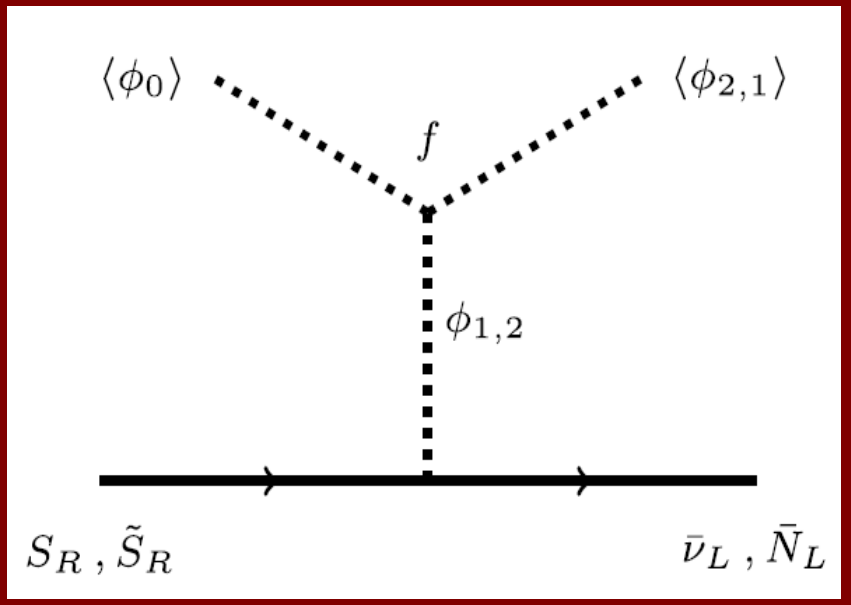
TABLE I. Matter content of the model, where $\hat{u}_R \equiv (u_R, c_R, t_R, t'_R)$ and $\hat{d}_R \equiv (d_R, s_R, b_R, d'_R, s'_R)$ (see text).

	ψ_L^ℓ	ℓ_R	$Q_L^{1,2}$	Q_L^3	$\hat{u}_R$	$\hat{d}_R$	S	ϕ_1	ϕ_2	ϕ_3
$SU(3)_c$	**1**	**1**	**3**	**3**	**3**	**3**	**1**	**1**	**1**	**1**
$SU(3)_L$	**3***	**1**	**3**	**3***	**1**	**1**	**1**	**3***	**3***	**3***
$U(1)_X$	$-\frac{1}{3}$	-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	$+\frac{2}{3}$	$-\frac{4}{3}$	$+\frac{2}{3}$

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

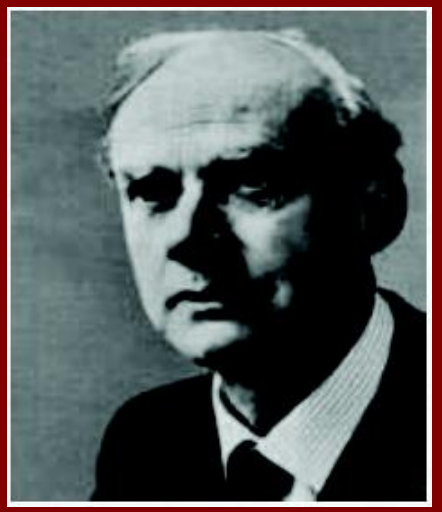
$$L = \frac{4}{\sqrt{3}} T_8 + \mathcal{L}. \qquad (3)$$

Type-II Dirac seesaw



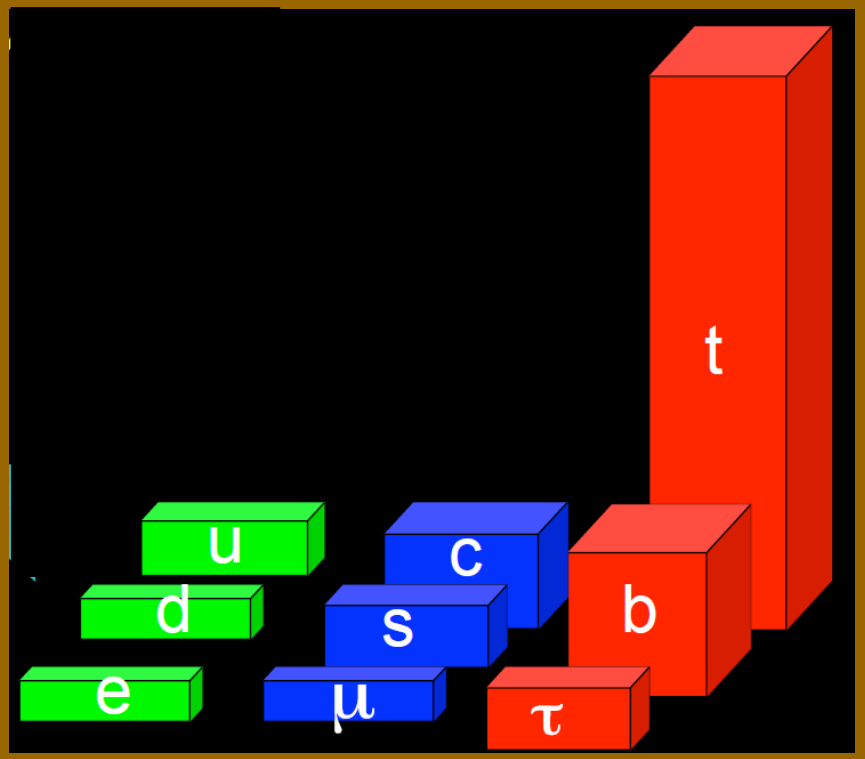
Physics Letters B 755 (2016) 363–366

arXiv:1605.08362



Flavor puzzle

masses



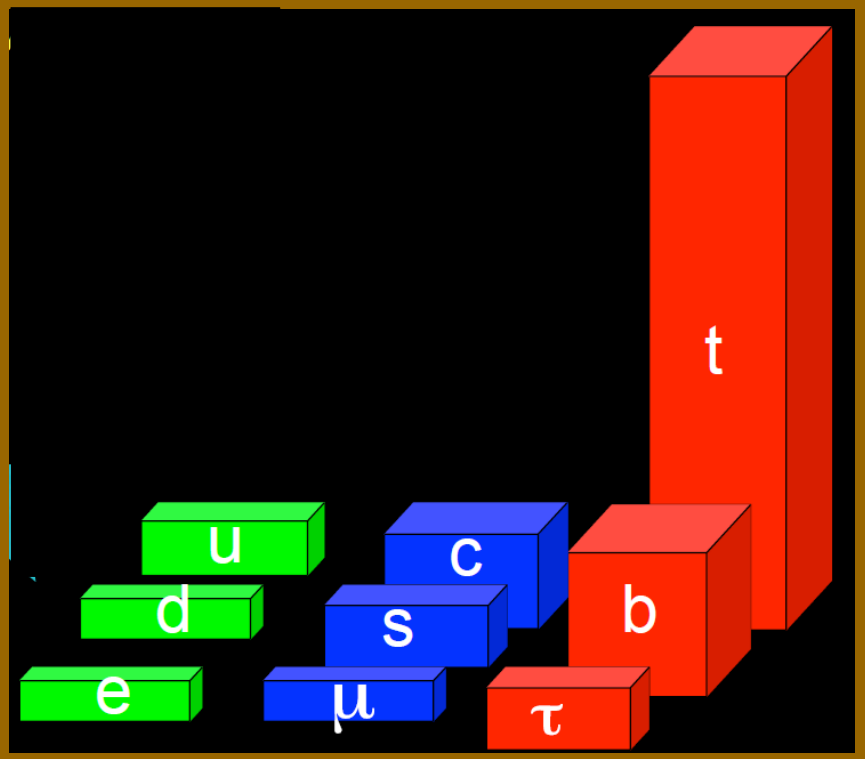
Neutrinos : Lepton number?

mixings

Flavor puzzle

masses

b-tau unification



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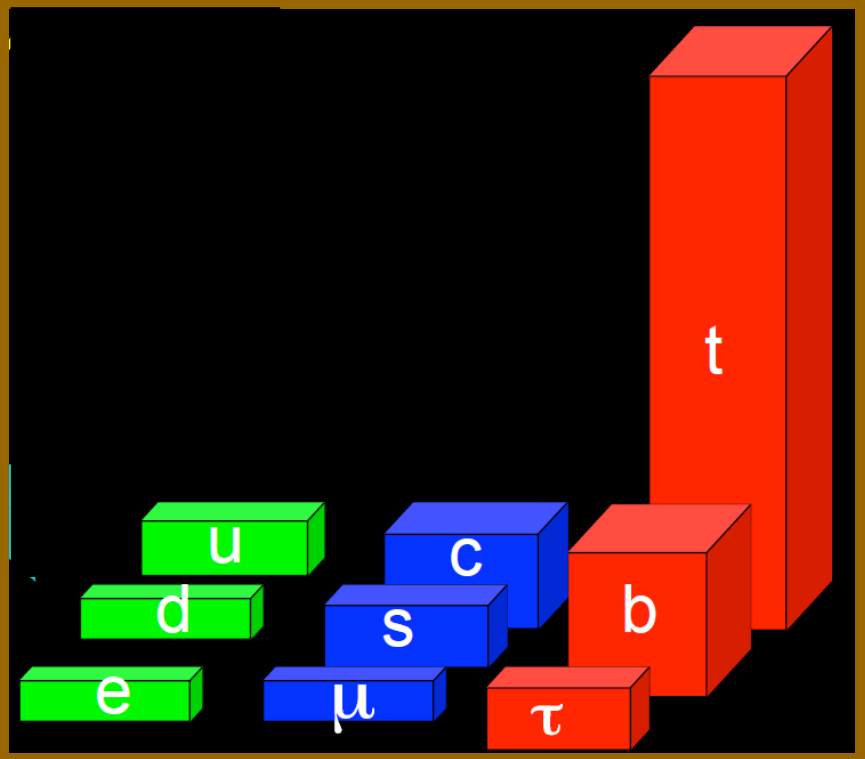

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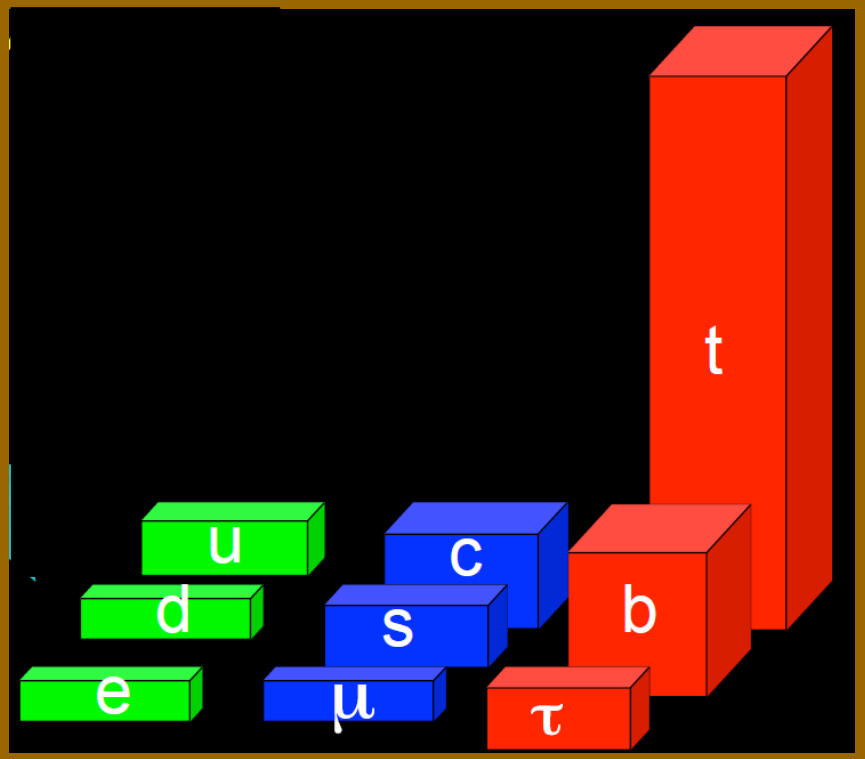

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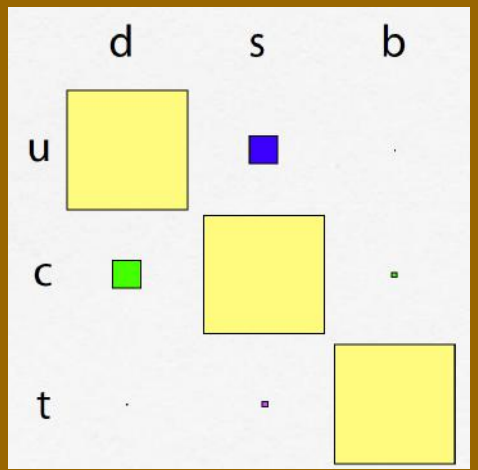
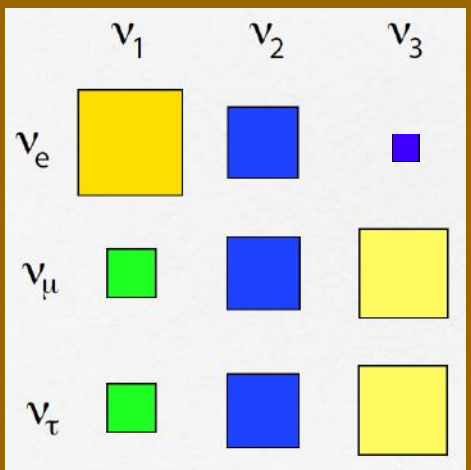


vs



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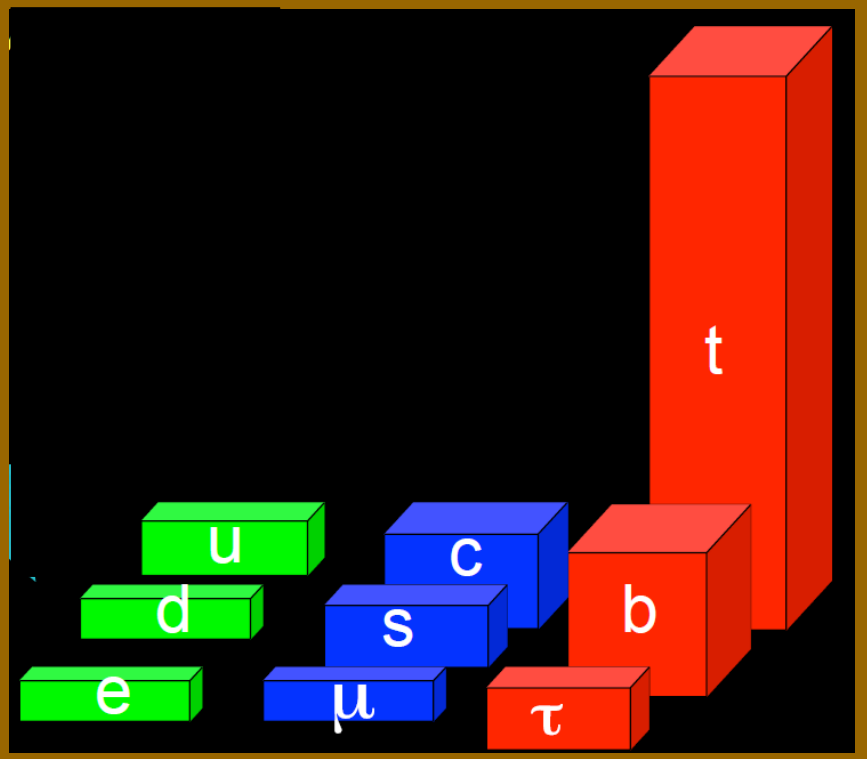

masses

b-tau unification without GUTS

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

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

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

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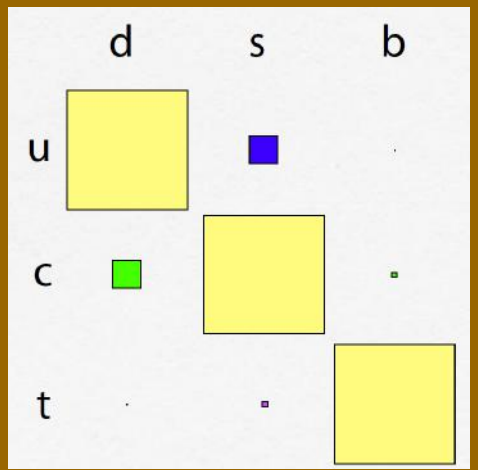
mixings



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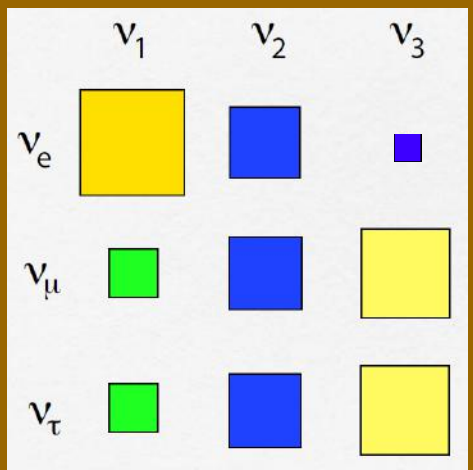
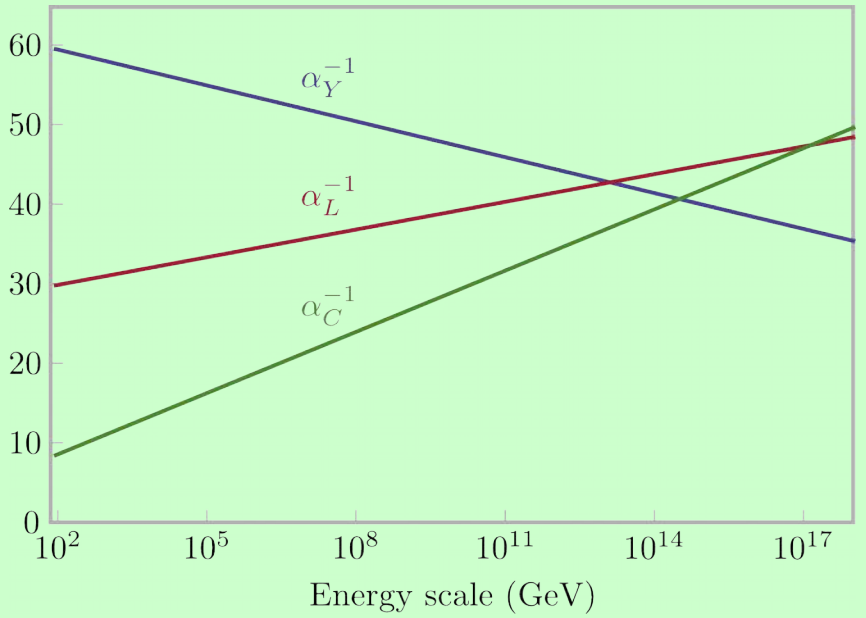


Gauge coupling unification

a near miss ...



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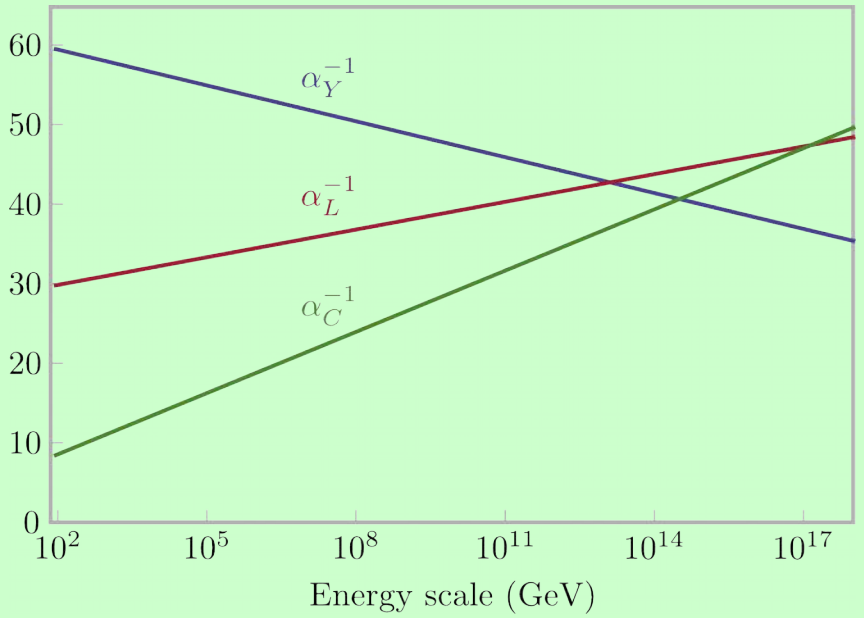
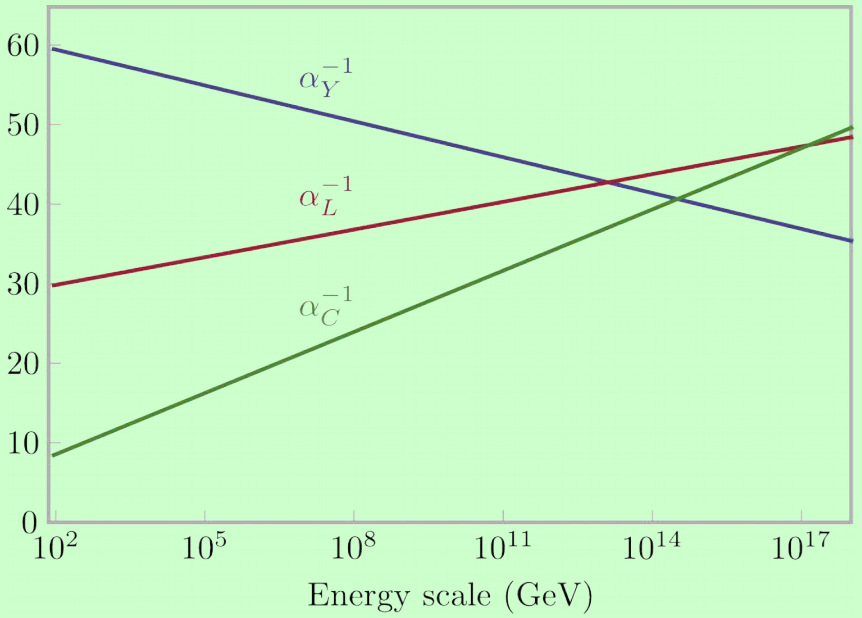


a near miss …

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

SUSY

Gauge coupling unification



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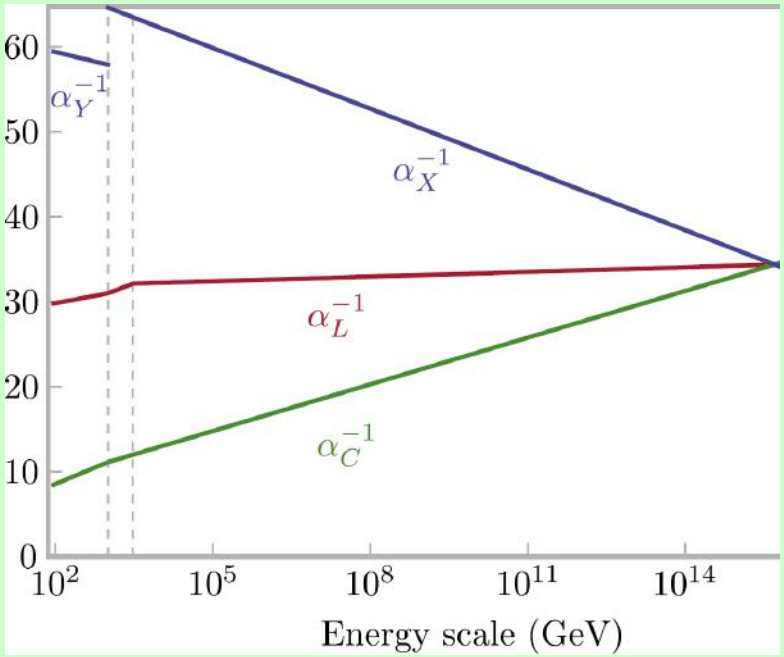
neutrino



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

Phys. Rev. D 91, 031702 (2015)

Boucenna, Fonseca, Gonzalez-Canales, JV

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

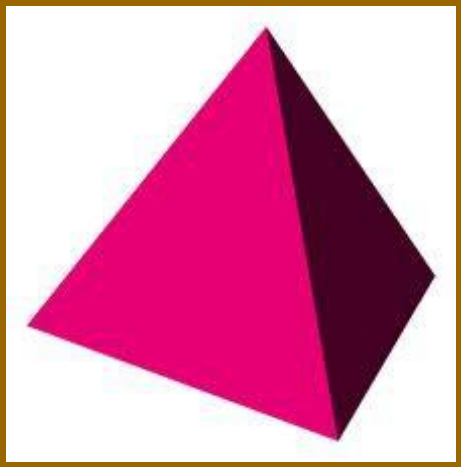
$$e_R \qquad \mu_R \qquad \tau_R$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \qquad c_R \qquad t_R$$

$$d_R \qquad s_R \qquad b_R$$

Flavor Symmetry



A4

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

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

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

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$$

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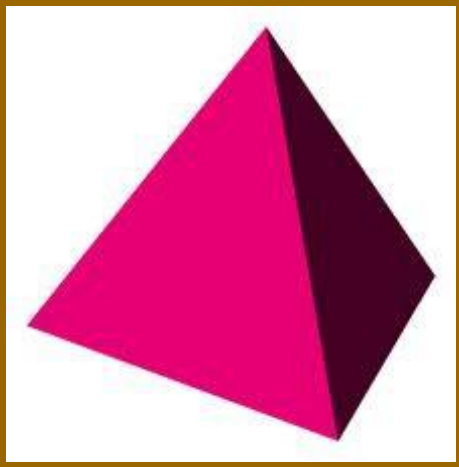

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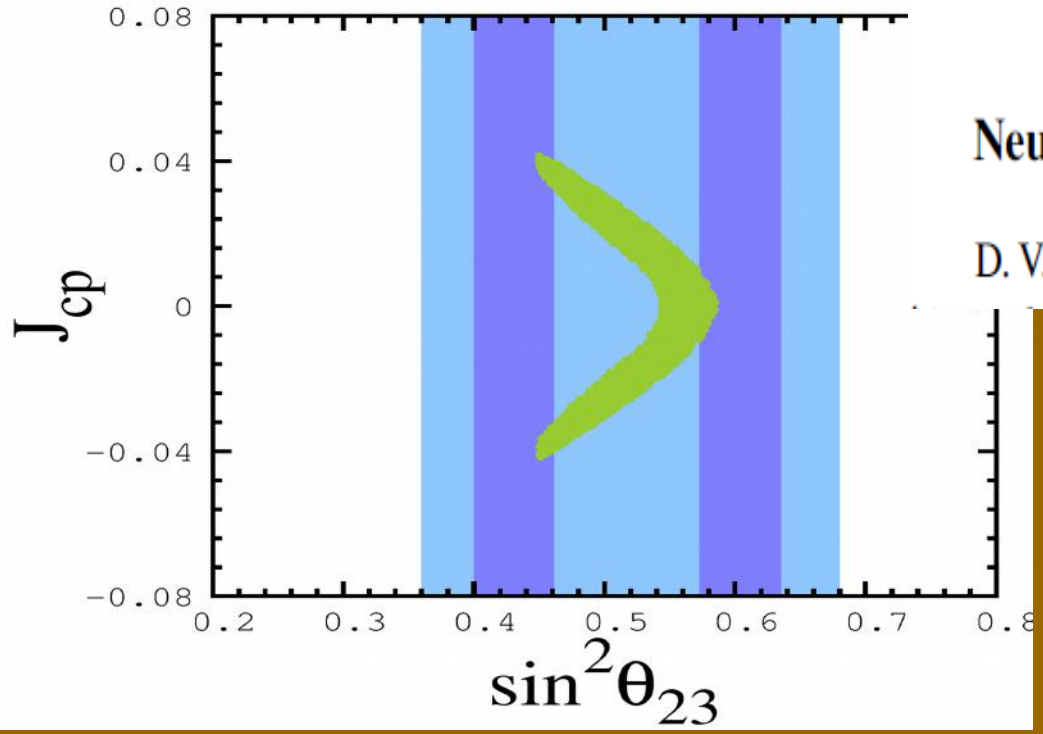


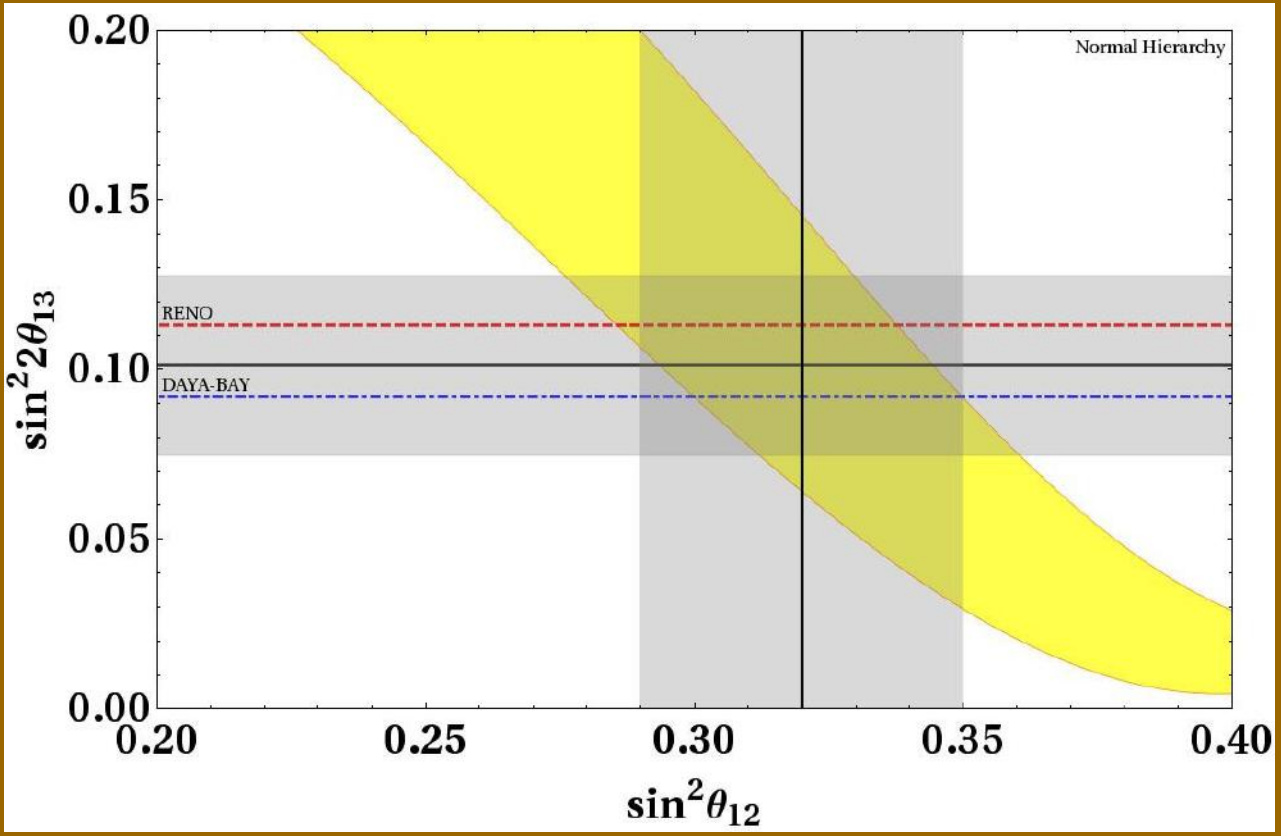
PHYSICAL REVIEW D 88, 016003 (2013)

Neutrino mixing with revamped A_4 flavor symmetry

D. V. Forero,[1,2,*] S. Morisi,[3,†] J. C. Romão,[1,‡] and J. W. F. Valle[2,§]

Flavor correlations

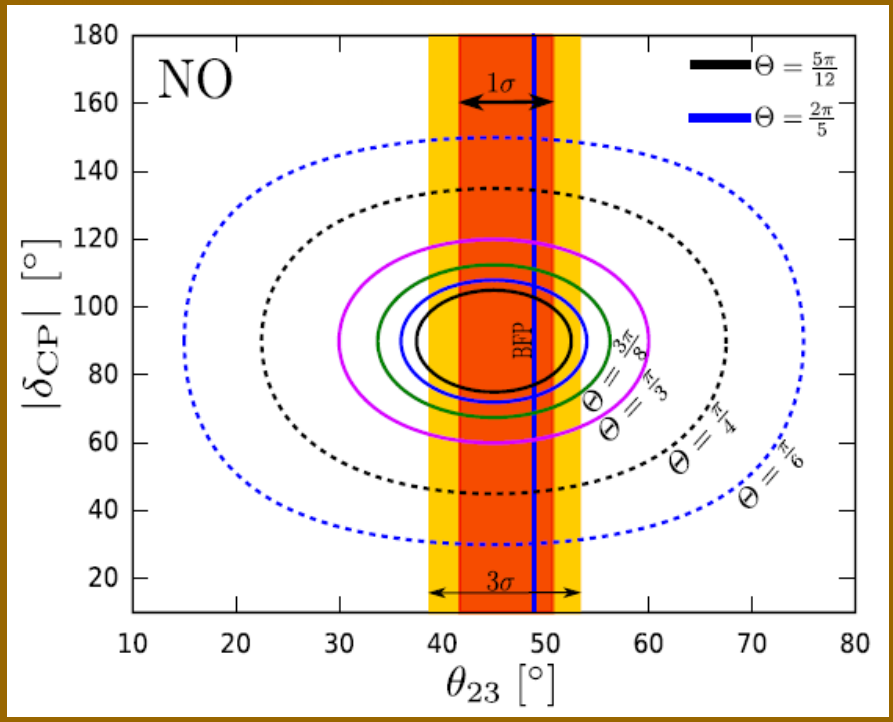
Boucenna et al
PhysRevD.86.073008



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

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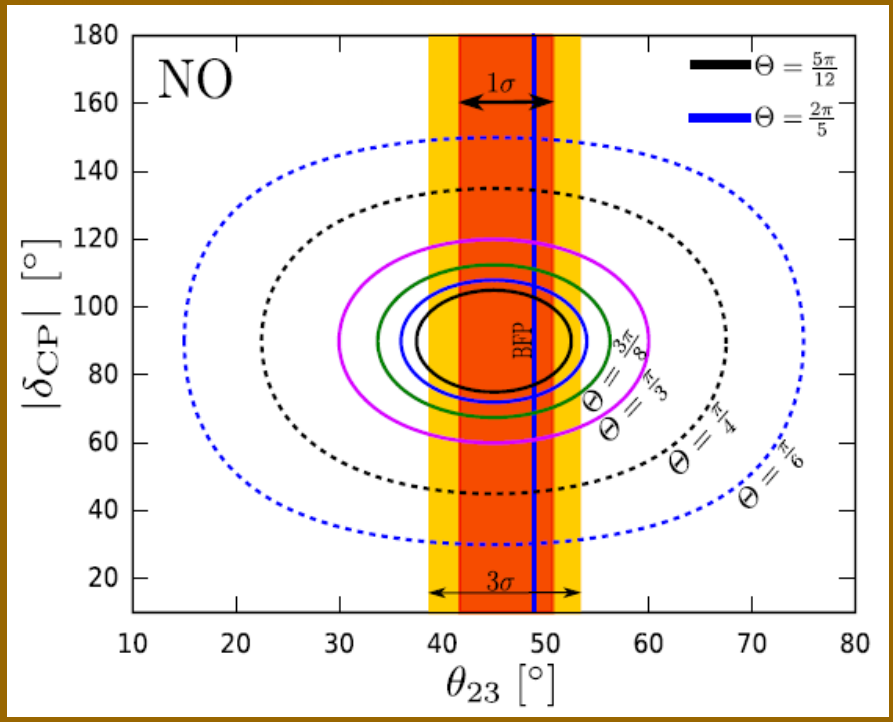
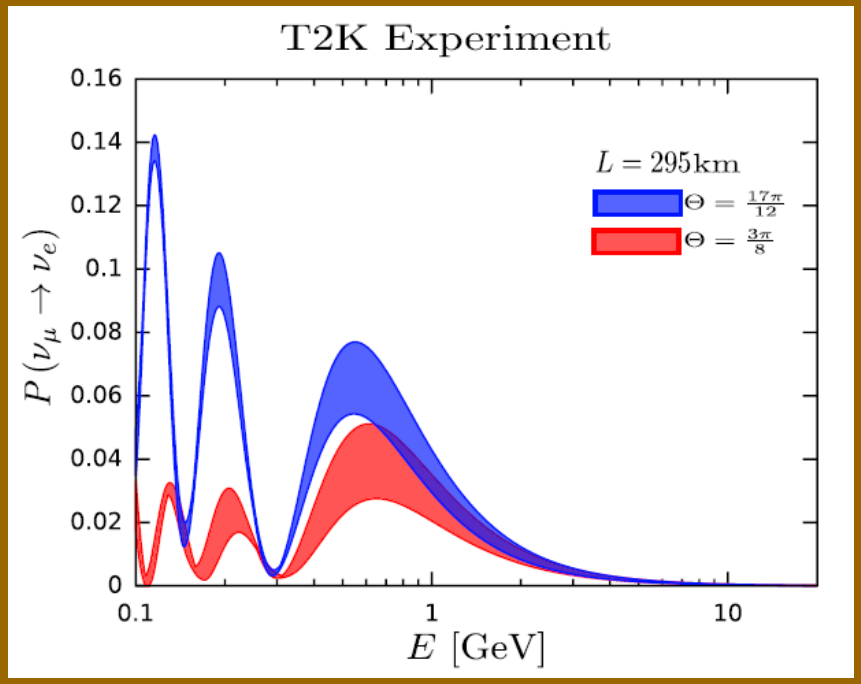
Predicting neutrino mixing from residual CP symmetries

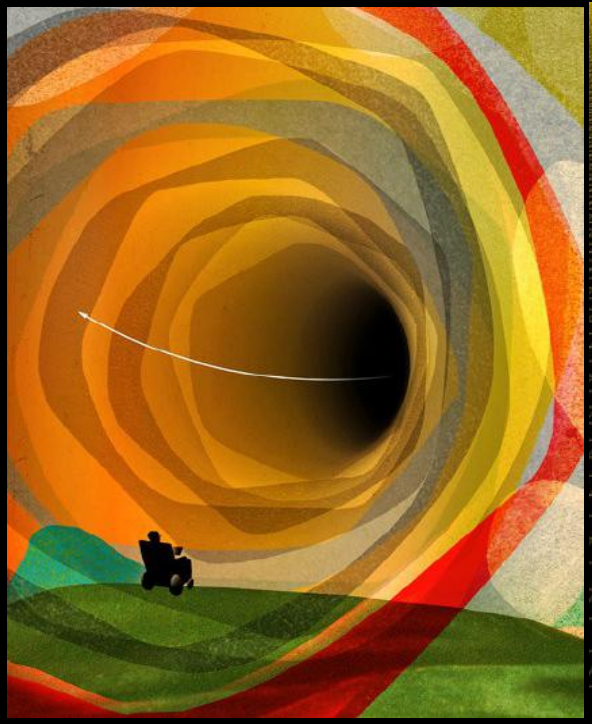


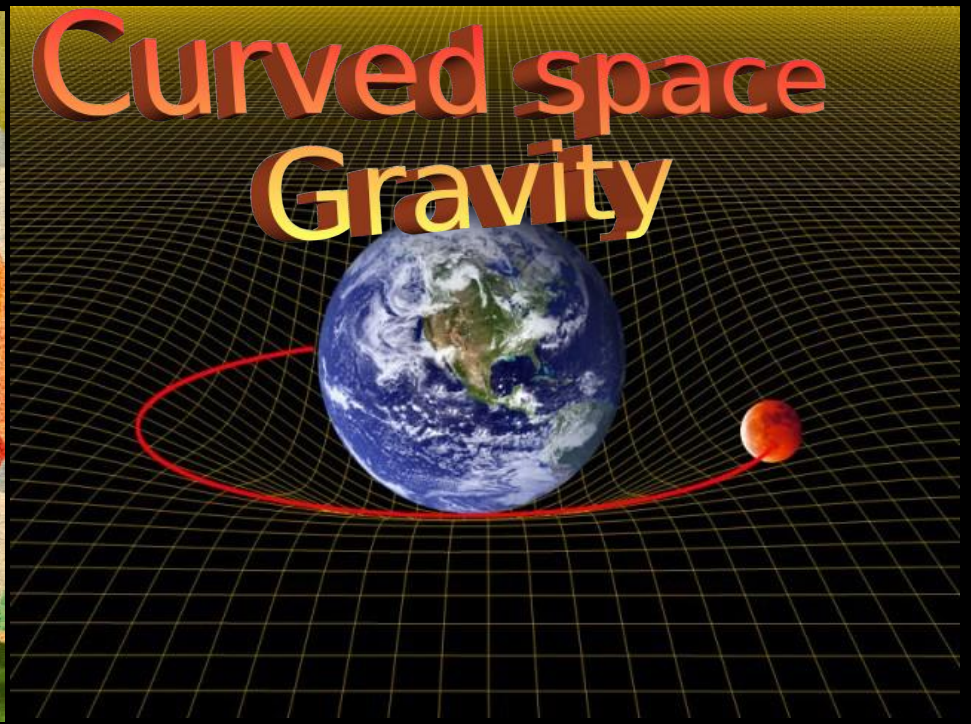


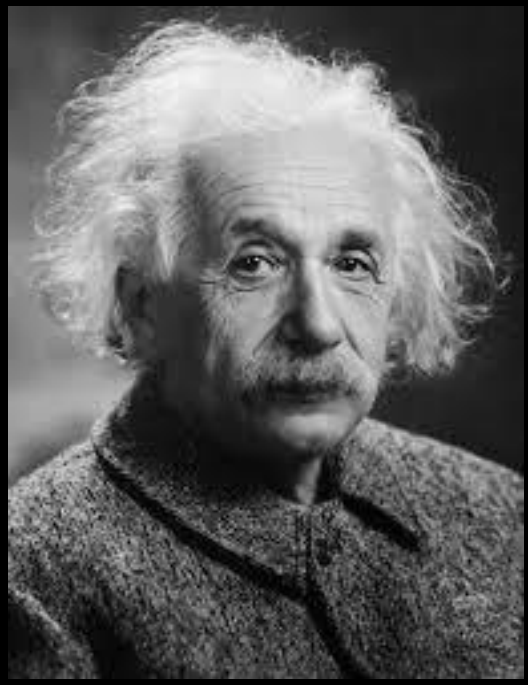
NOVA, DUNE

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

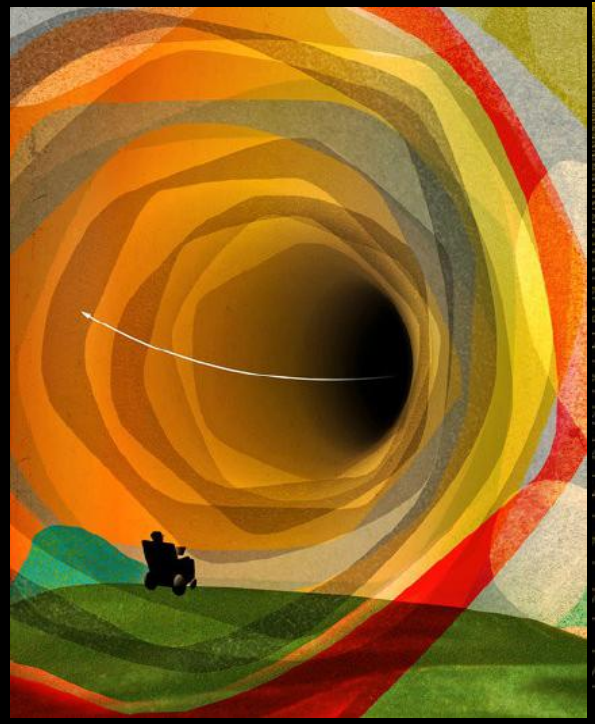
How about gravity?



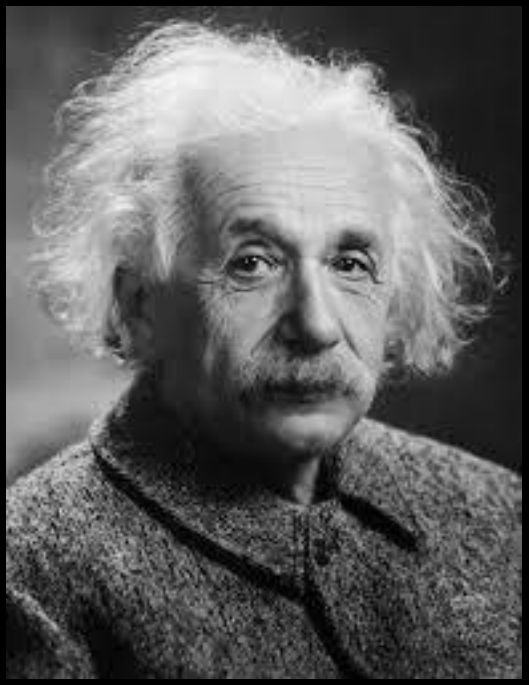




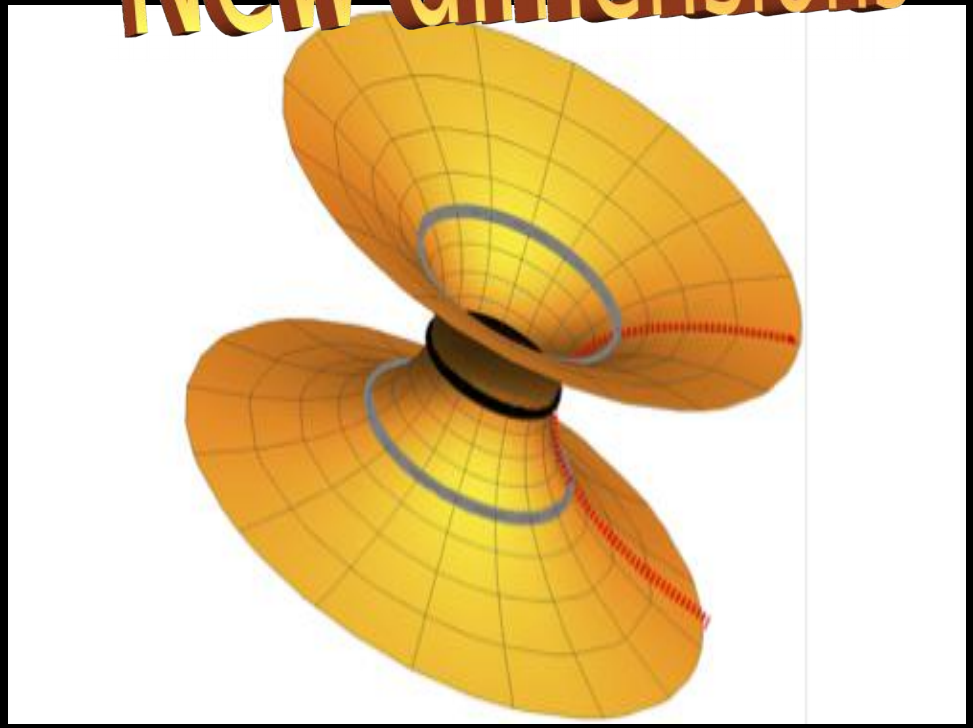
Valle



Curved space
Gravity



New dimensions

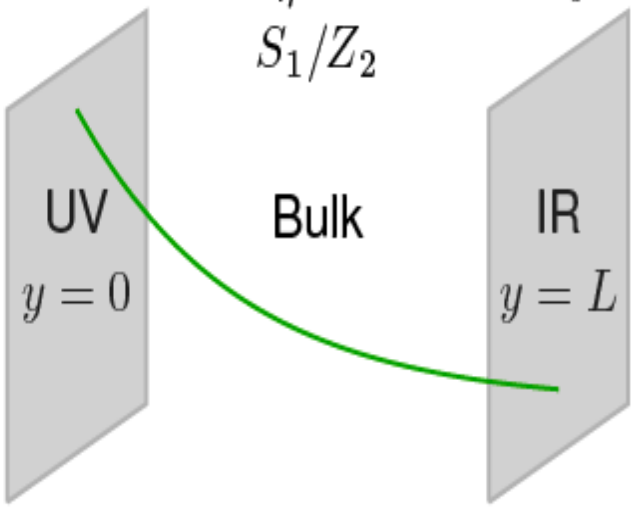


Warped flavor

: Chen et al arXiv:1509.06683
JHEP01(2016)007

Randall-Sundrum brane-world

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



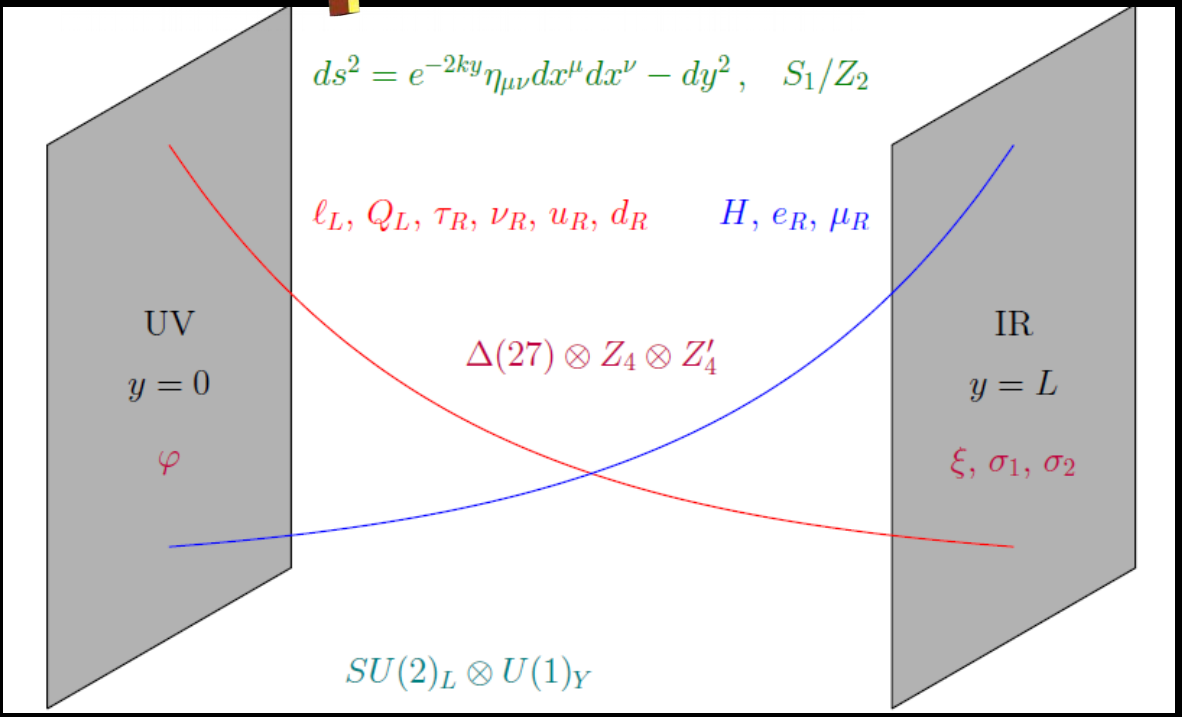
5D field theory on a slice of AdS_5

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

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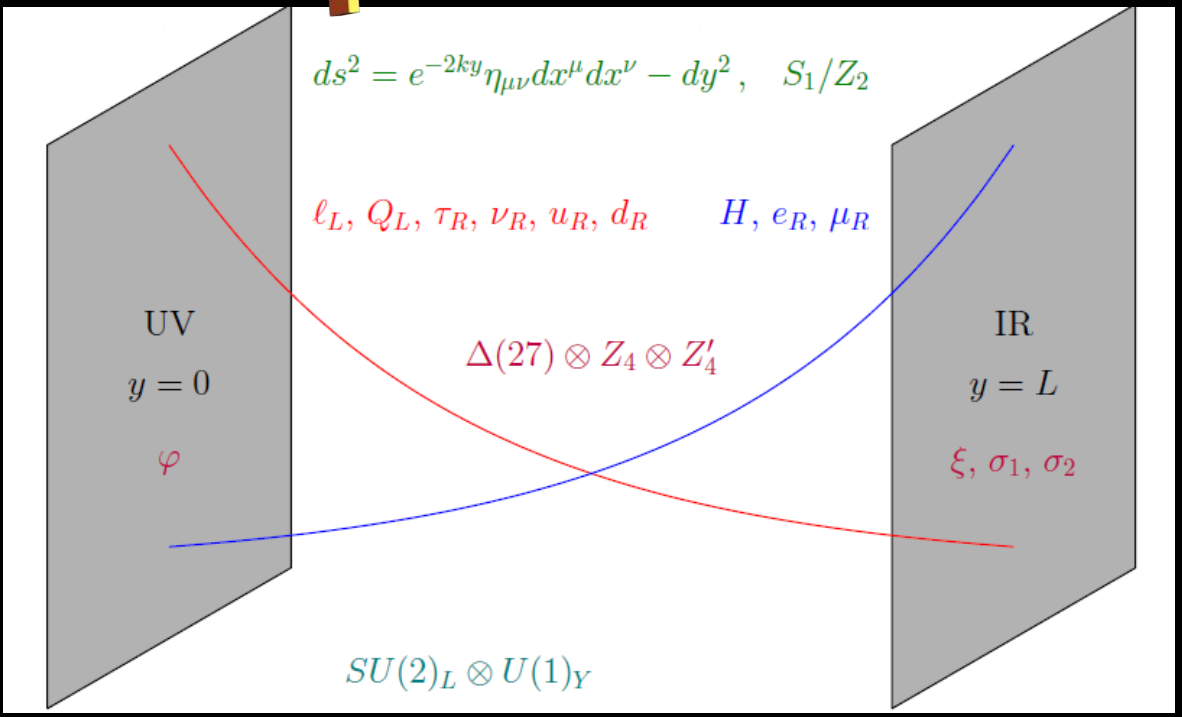

Mass hierarchies in principle accounted for by judicious bulk parameter choices

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

4 neutrino mixing angles & CP phase in terms of **2**

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

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

Warped flavor

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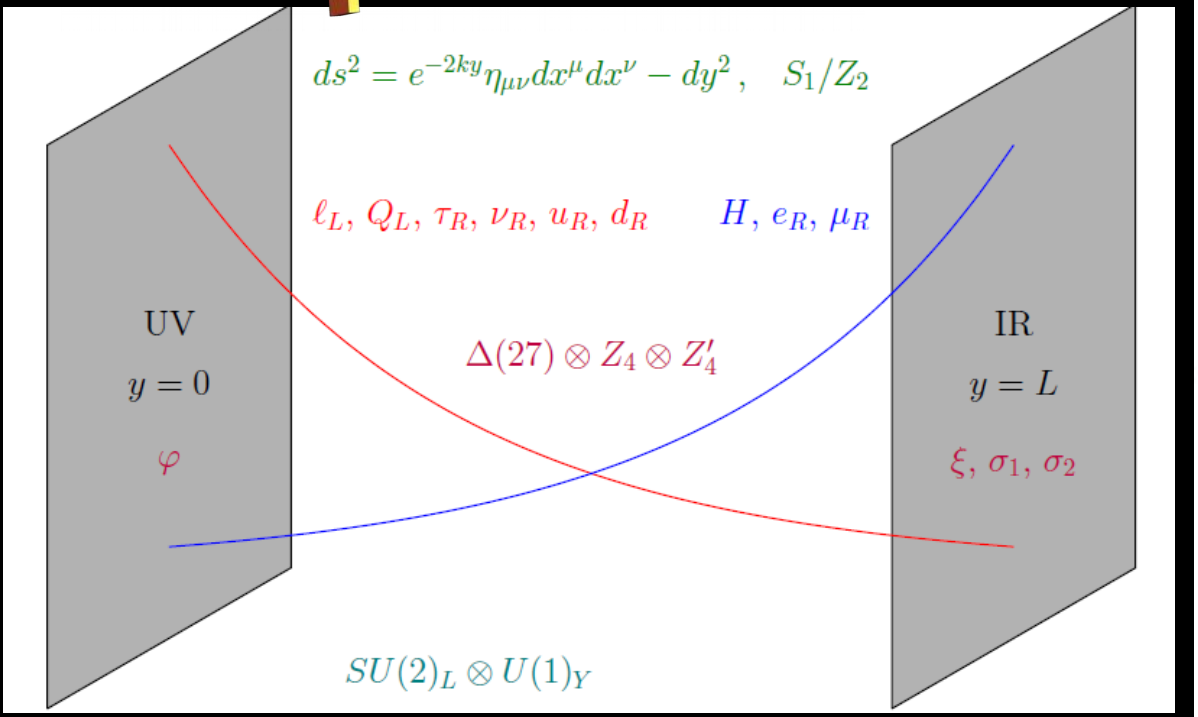

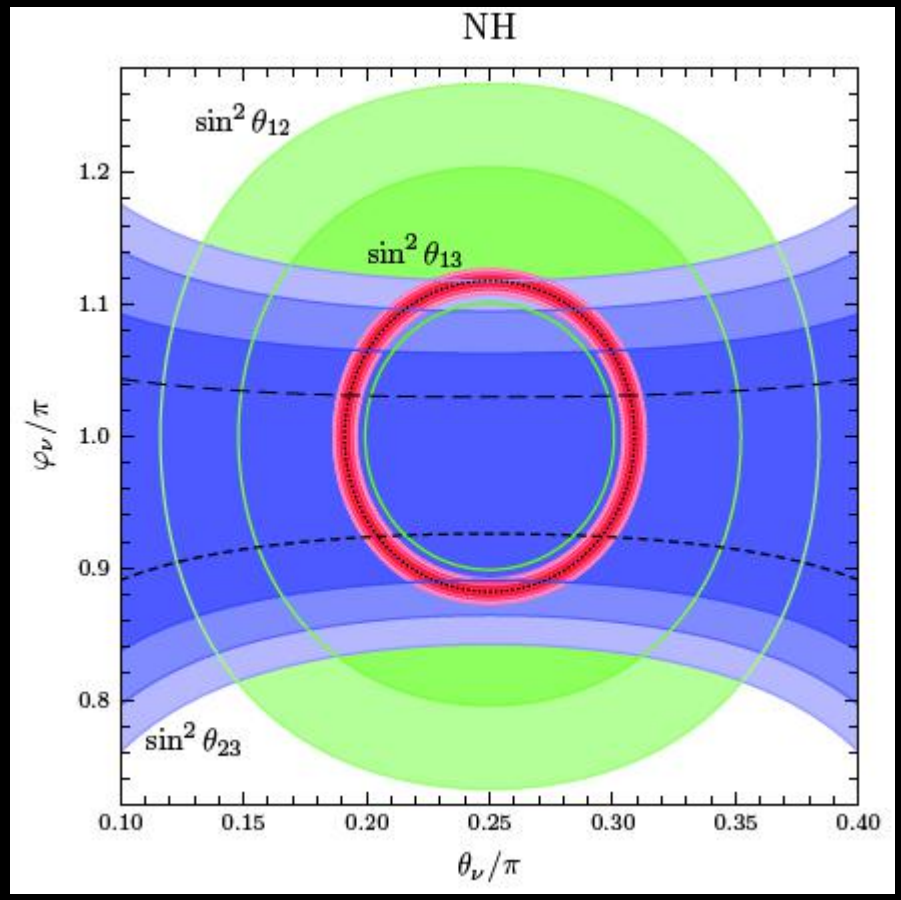

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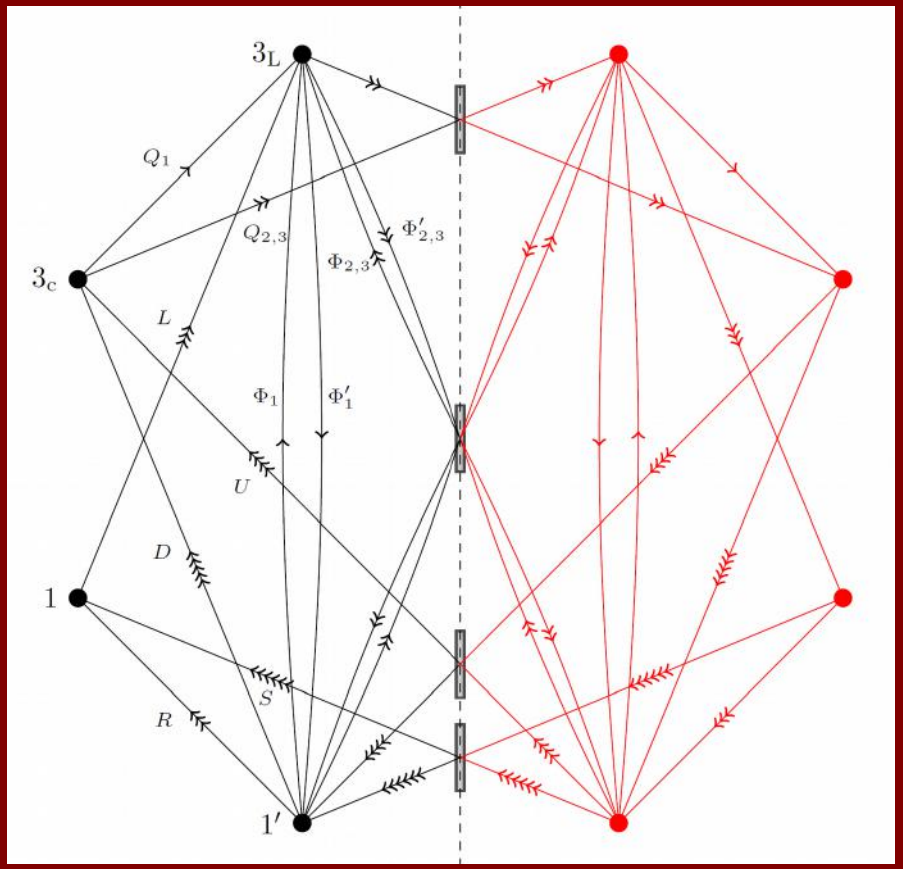
String completion of 331



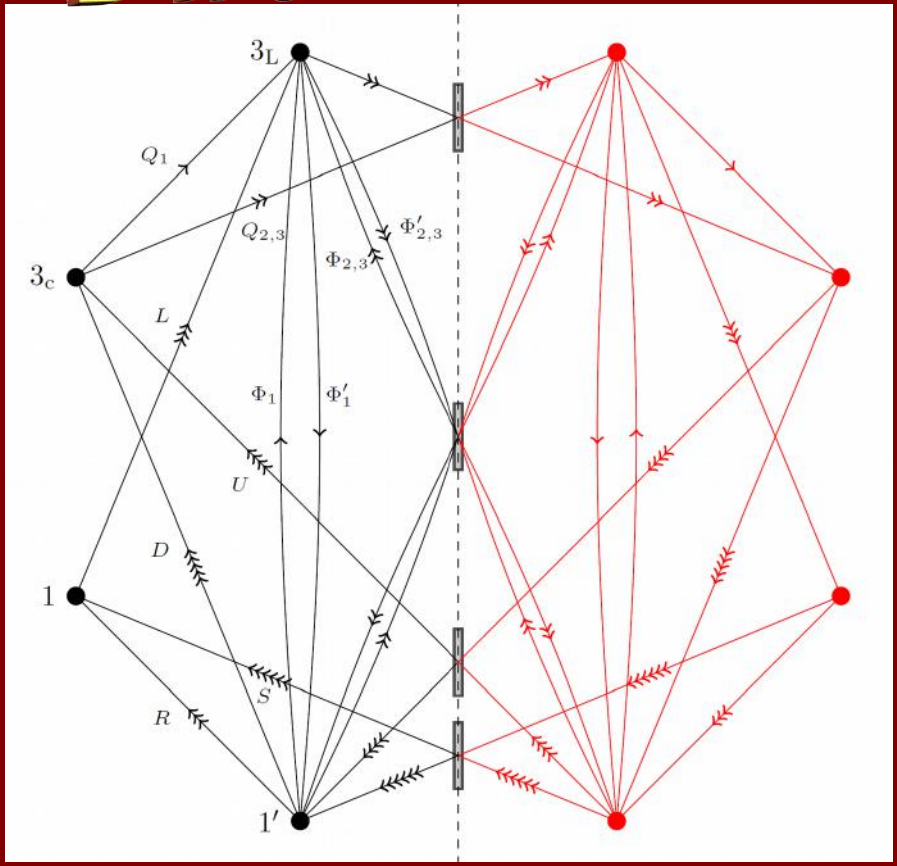
Addazi et al Phys.Lett. B759 (2016) 471-478

string completion of EW model with No conventional GUT embedding

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

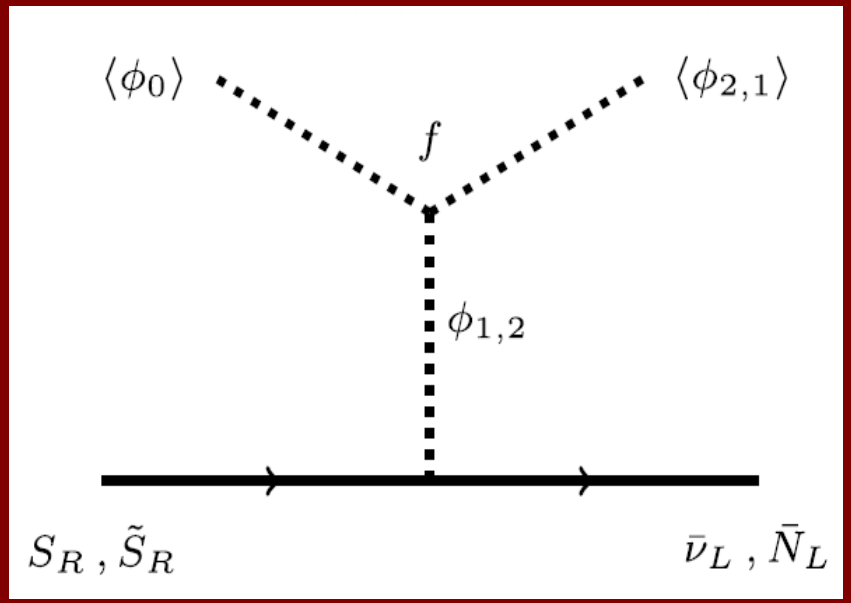
no p decay, no RPV … neutron-antineutron oscillations added from exotic instantons

Dirac seesaw



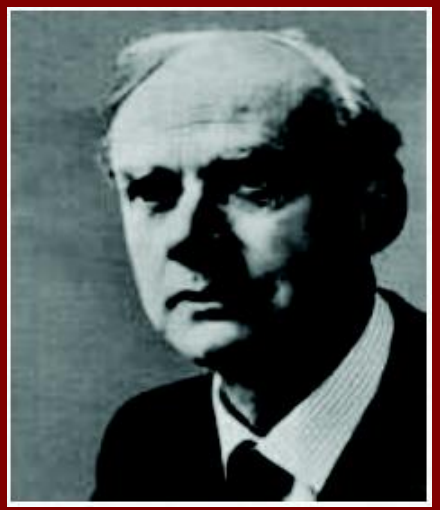
Addazi et al arXiv:1604.02117

From strings



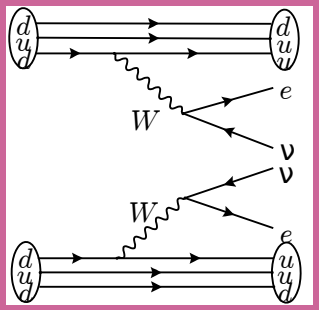
Physics Letters B 755 (2016) 363–366

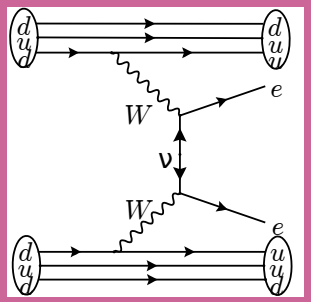
arXiv:1605.08362



A.S. Barabash arXiv:1104.2714

Neutrinoless double beta decay





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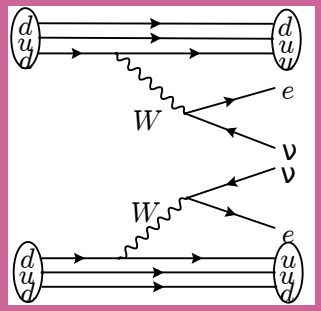

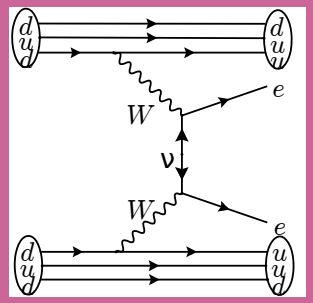

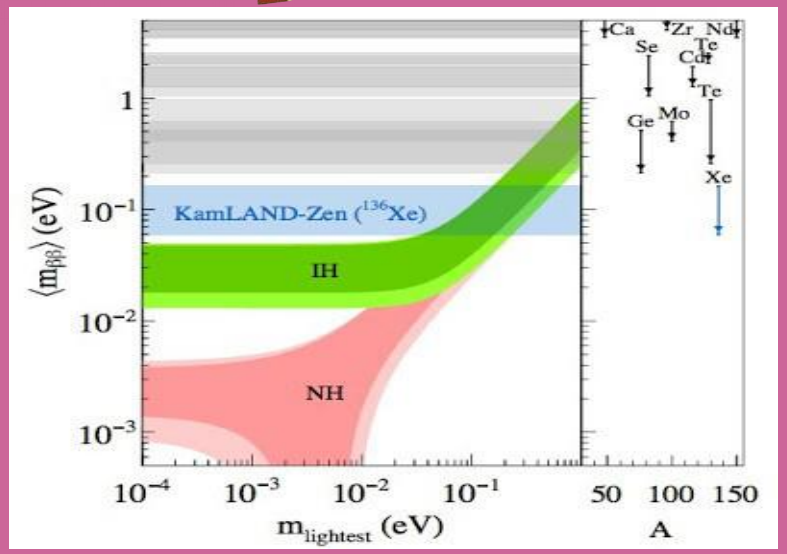

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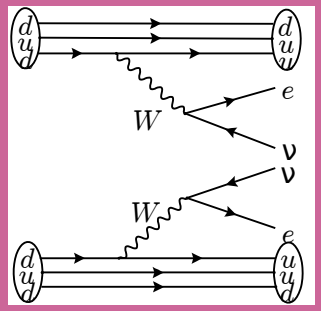

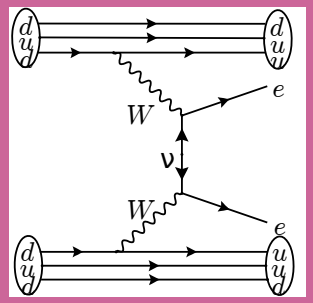

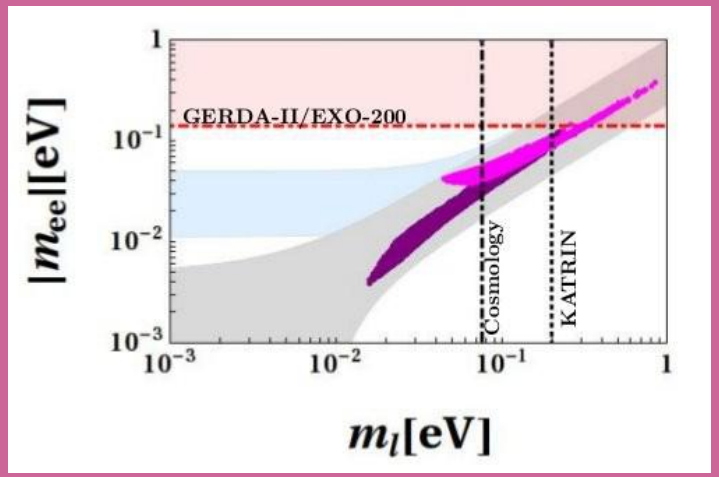

Flavor Sensitivity

Bonilla et al arXiv:1411.4883

A.S. Barabash arXiv:1104.2714

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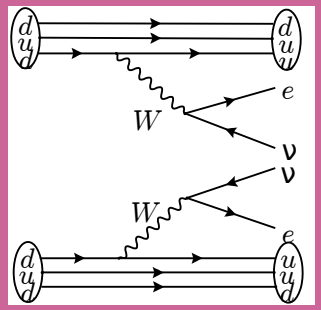

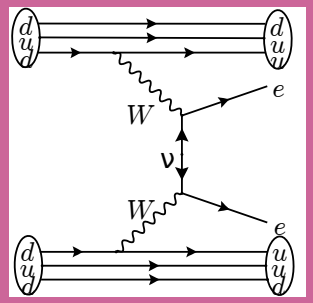

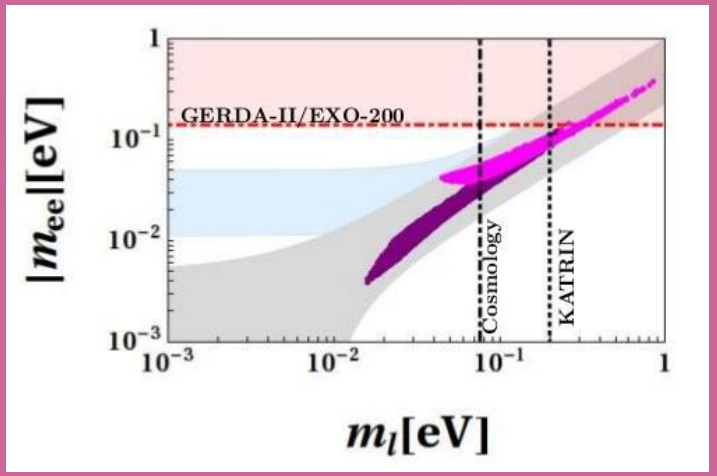

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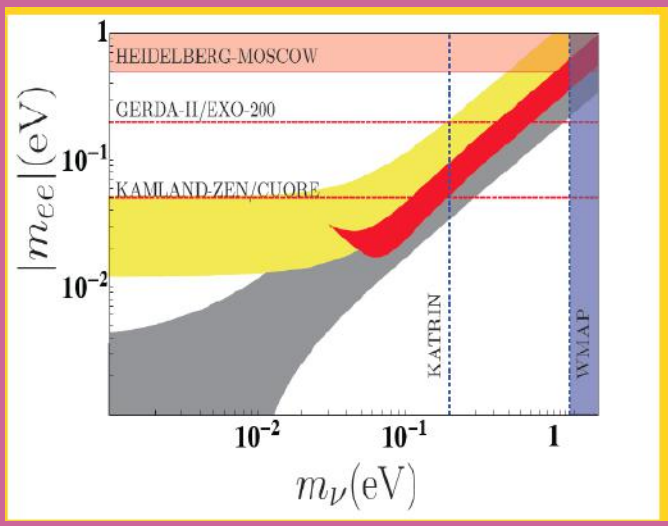
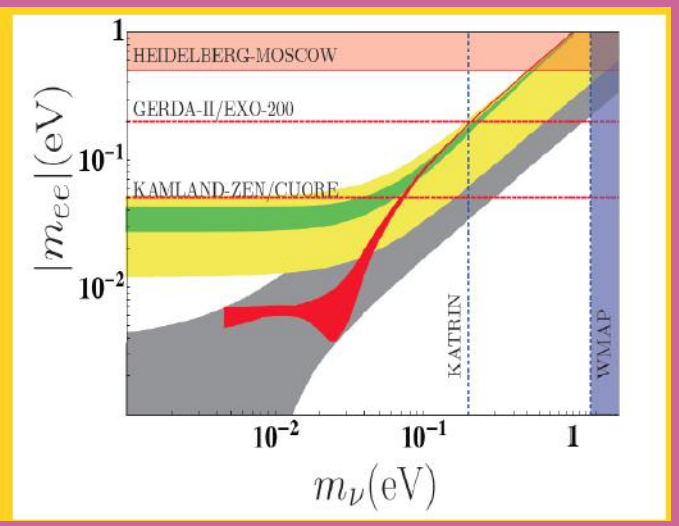
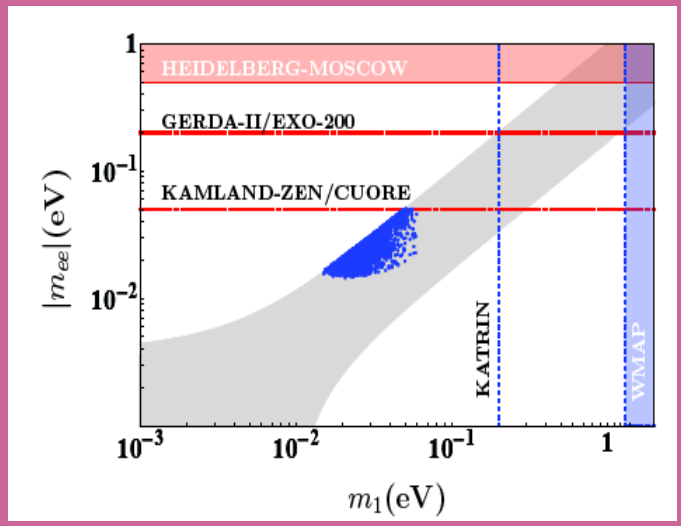




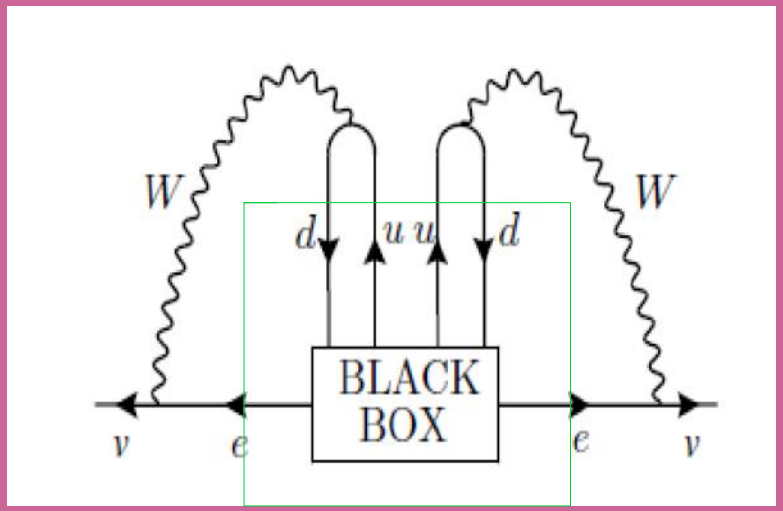


Dorame et al
NPB861 (2012) 259-270

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

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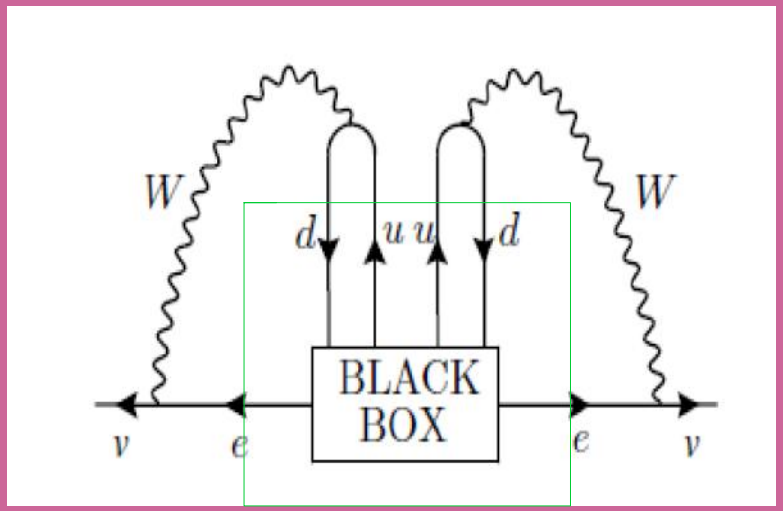

Even if mediated by short-range mechanism ...

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Heavy mediators at the LHC

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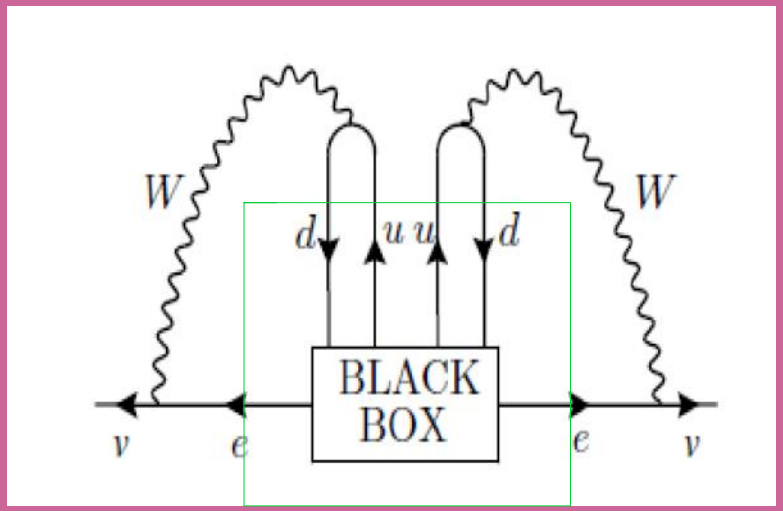

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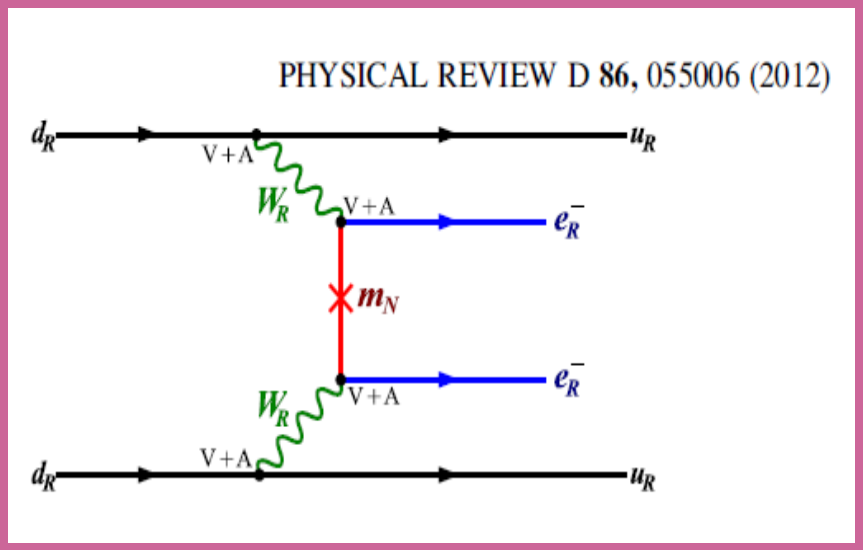
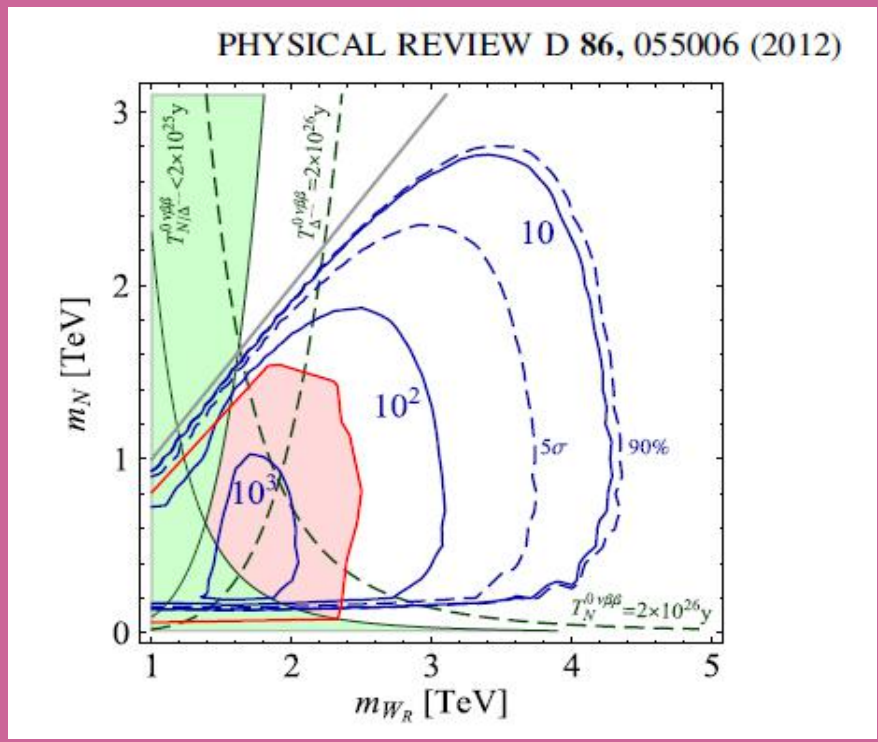


Valle



SM vacuum

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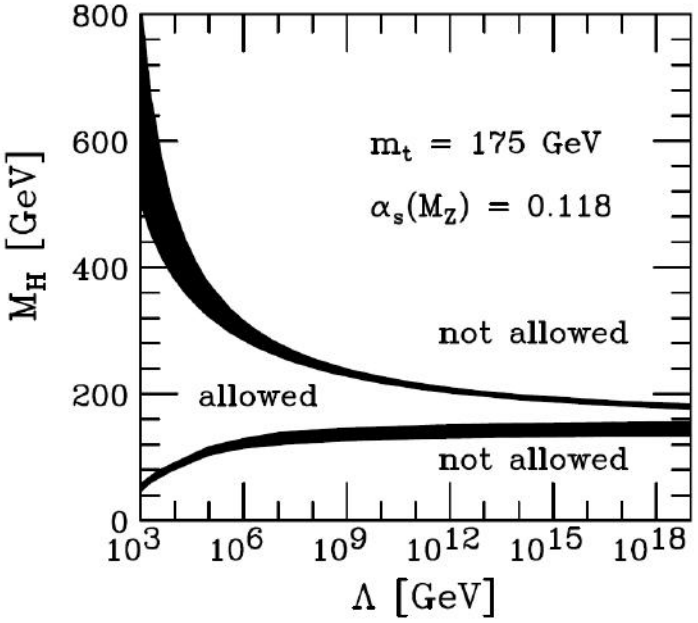
SM vacuum



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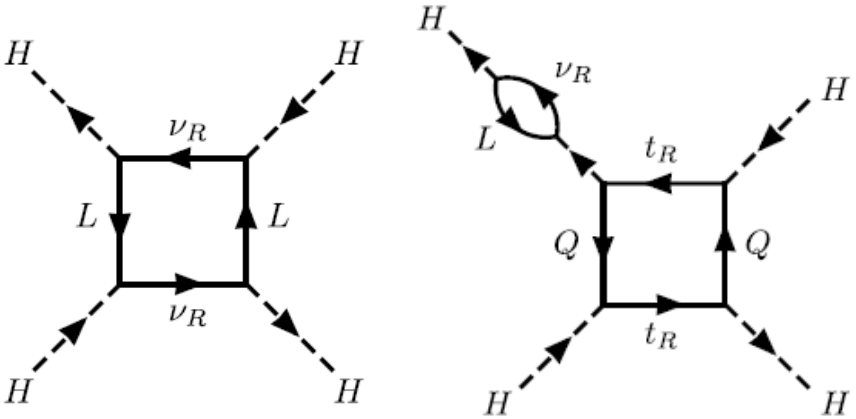
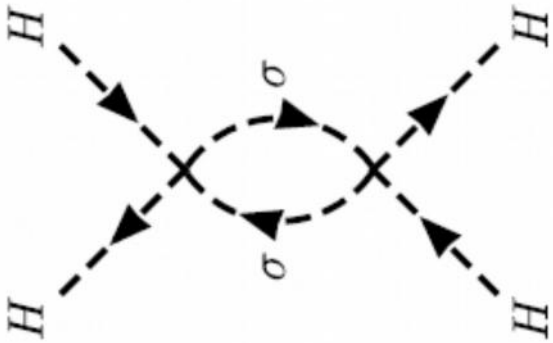
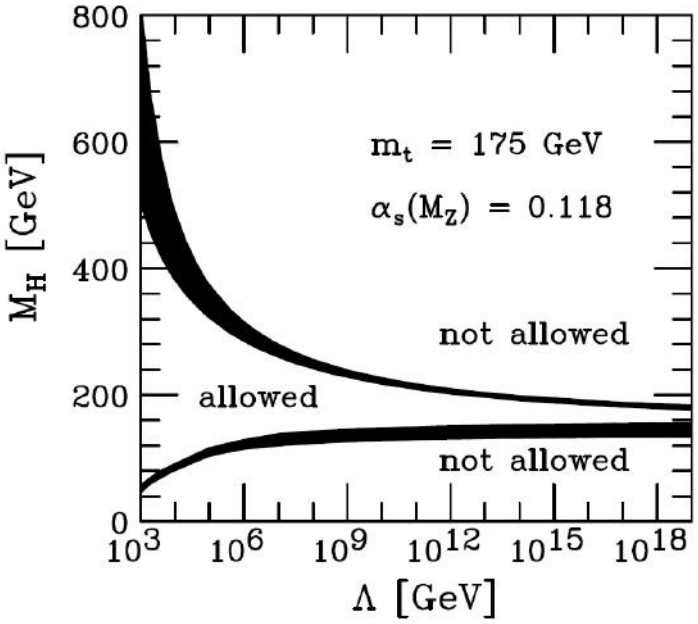
SM vacuum and neutrinos

Physics Letters B 756 (2016) 345–349







Valle

PHYSICAL REVIEW D **91,** 113015 (2015)

Neutrino mass and invisible Higgs decays at the LHC

Cesar Bonilla,[1,*] Jorge C. Romão,[2,†] and José W. F. Valle[1,‡]

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

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

arXiv:1502.01649

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

Valle

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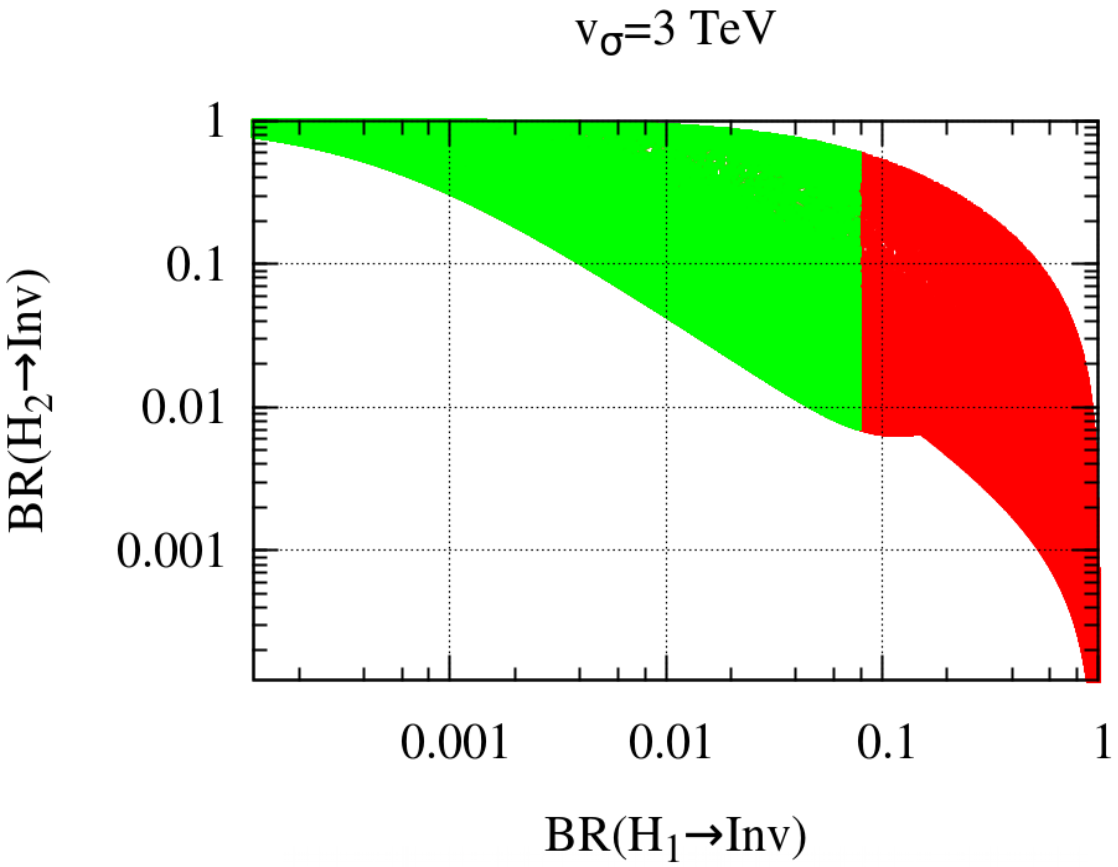


Valle

Neutrino as higgs benchmark

Why neutrinos

The road to new physics

Why neutrinos

The road to new physics

diphoton

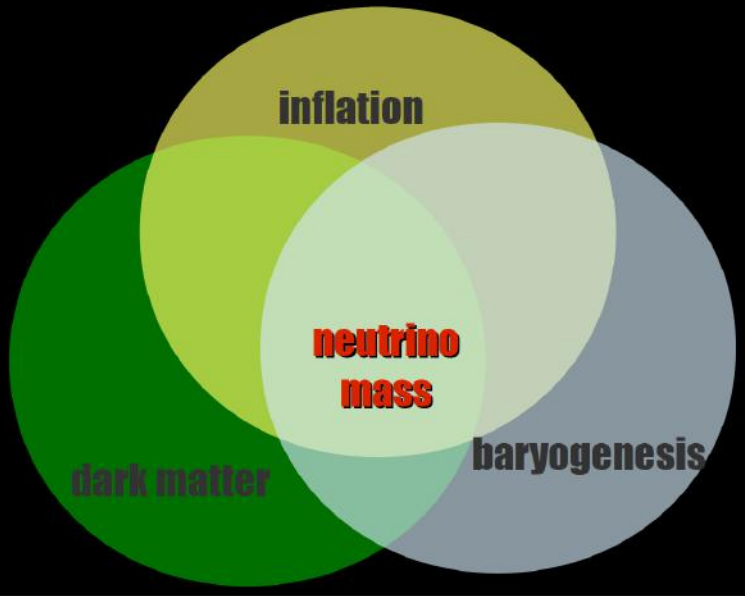
Why neutrinos

The road to new physics

Basic cosmo & astro probe

May explain cosmo puzzles

diphoton

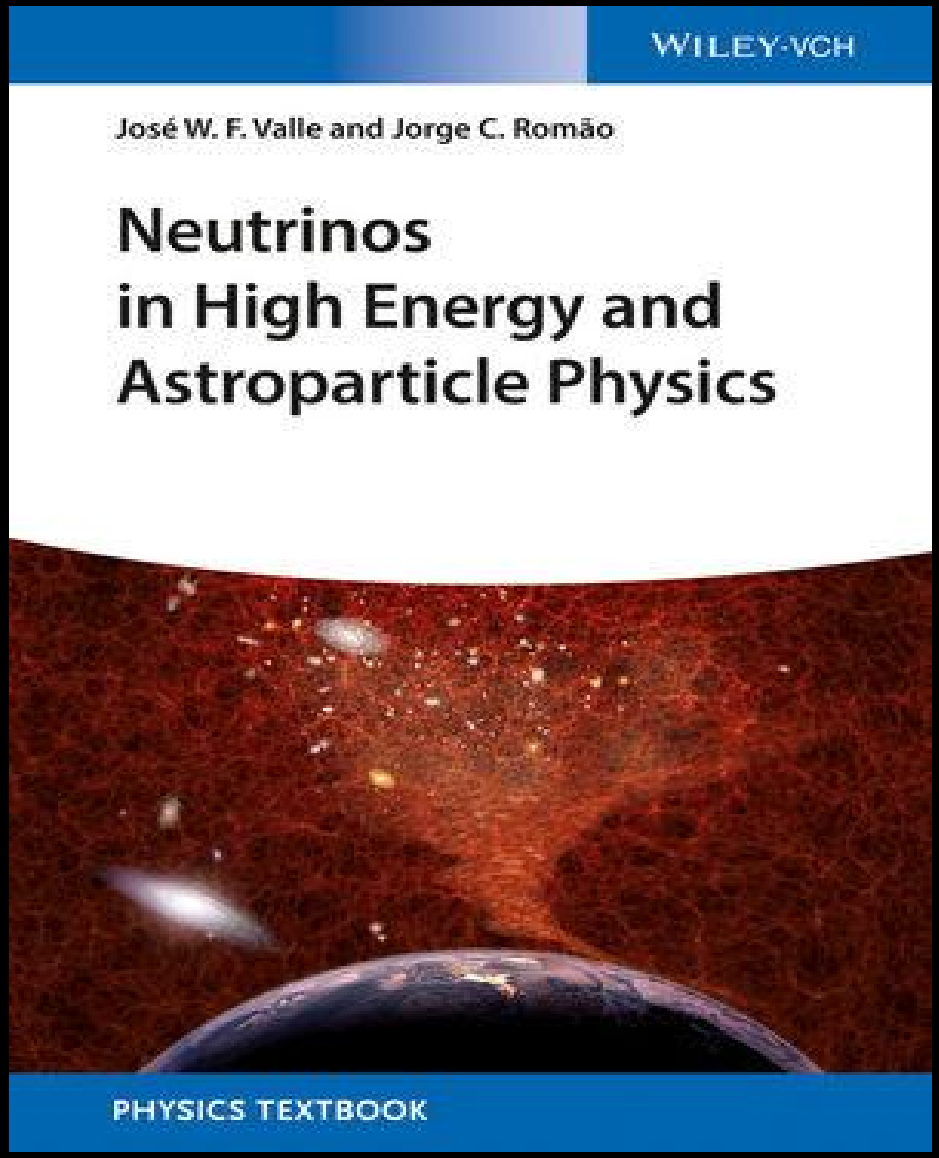


Thank you

http://t.co/yUSLiF1cGX

fb.me/2ZAD7khZf

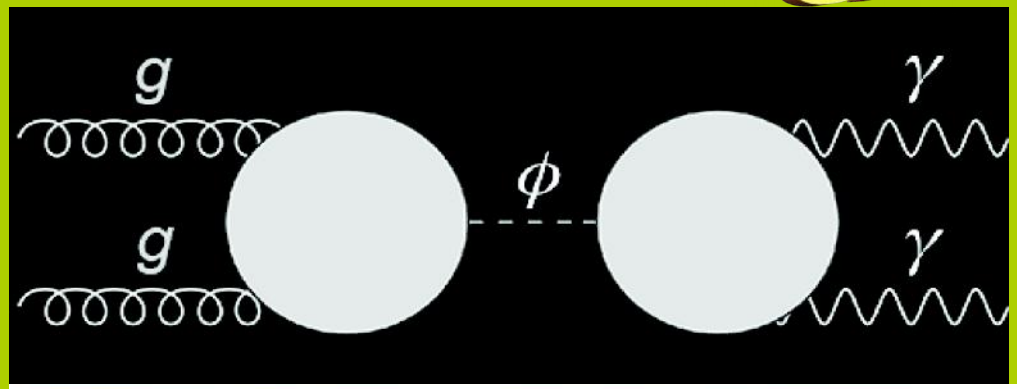
All you ever
Wanted to know
About neutrinos
As guide to
New physics

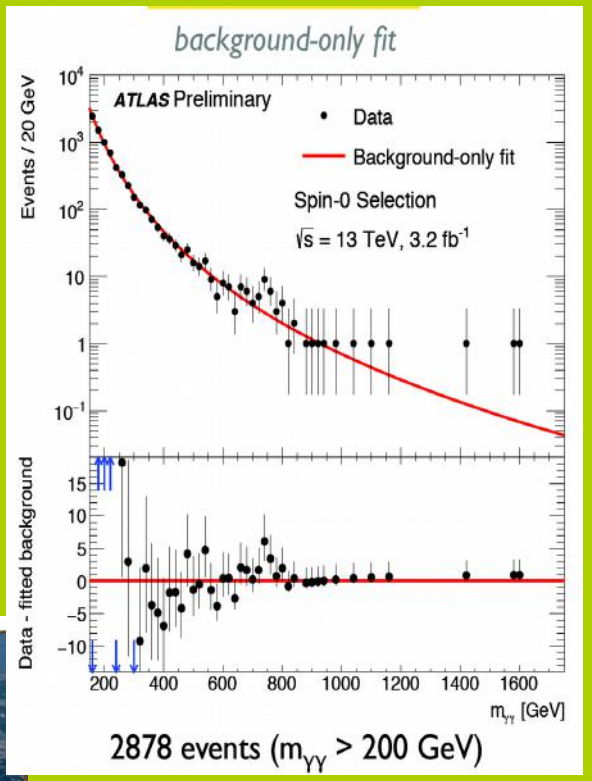


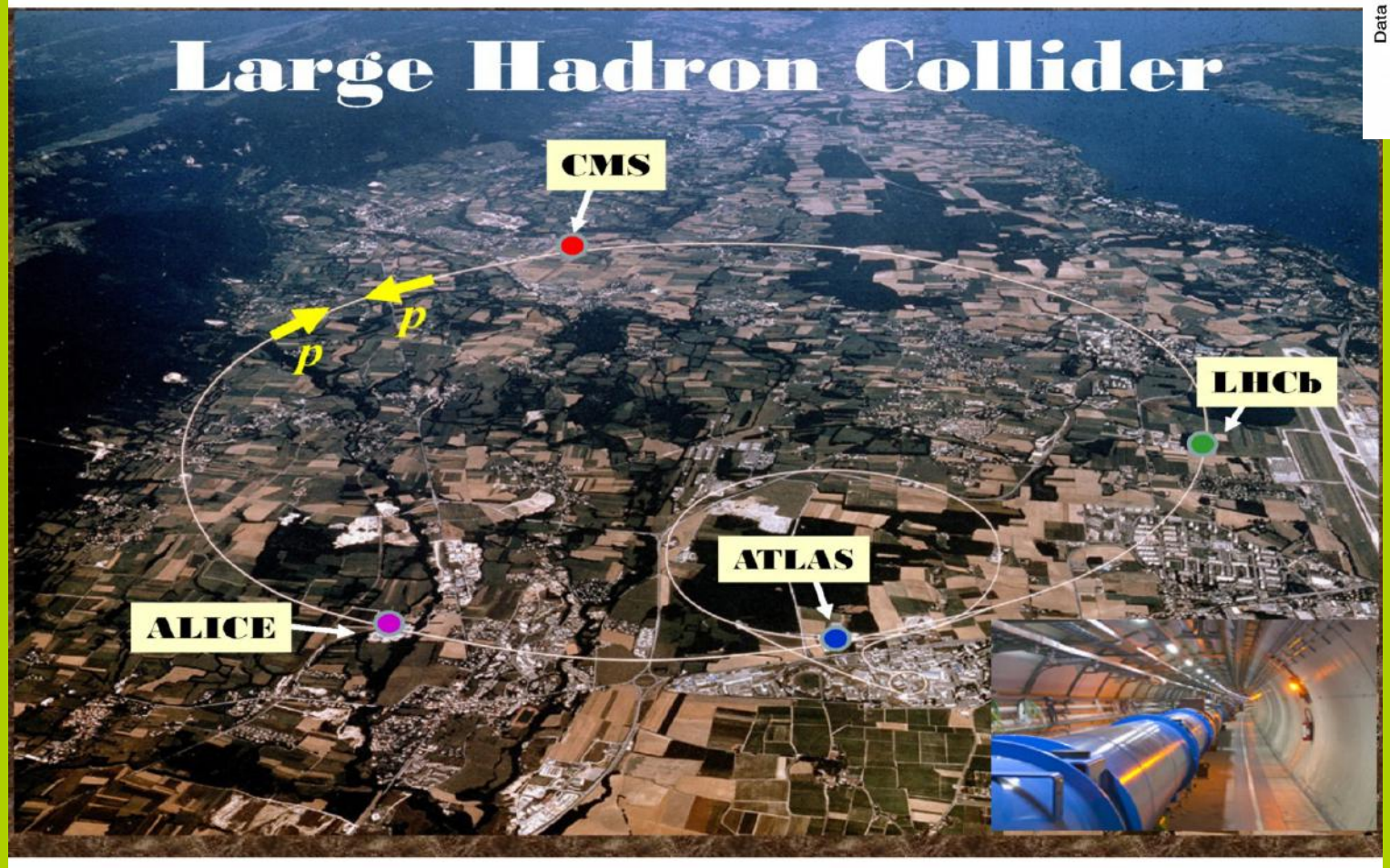
ISBN: 978-3-527-41197-9
458 pages
2015

Backup slides

Diphoton anomaly

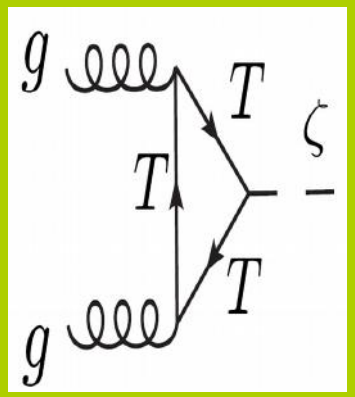




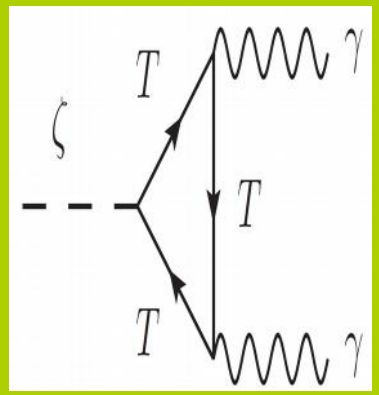


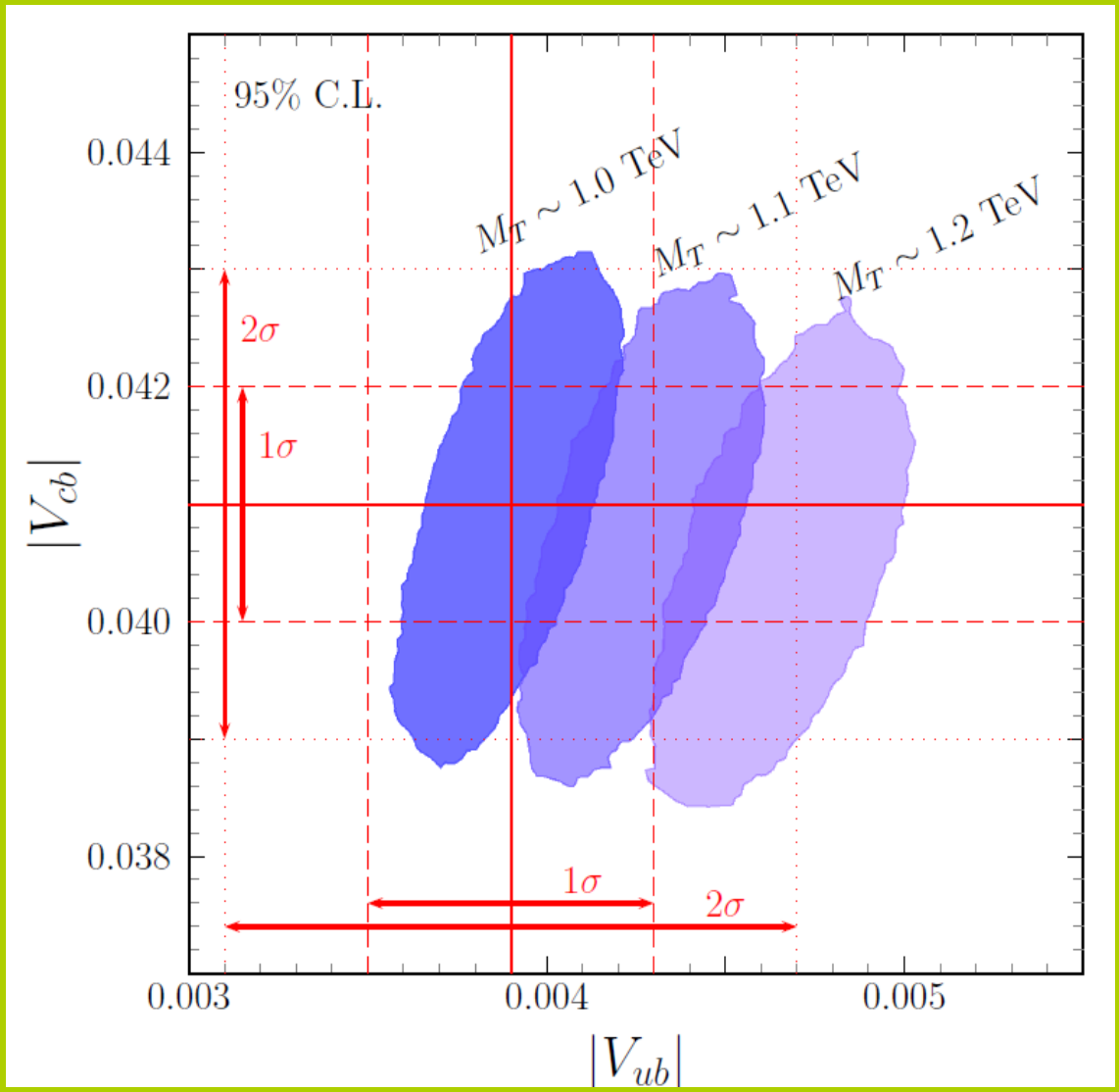
Diphoton anomaly

PhysRevD93, 073009 (2016)



As a flavon

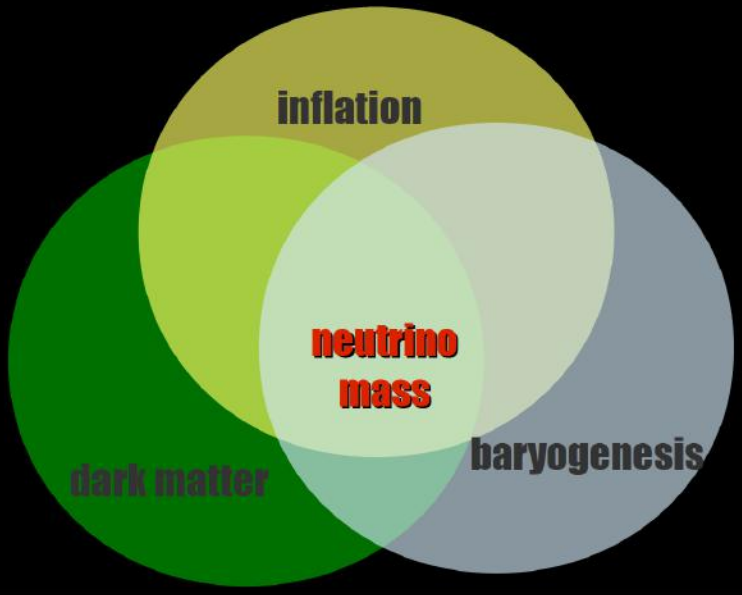


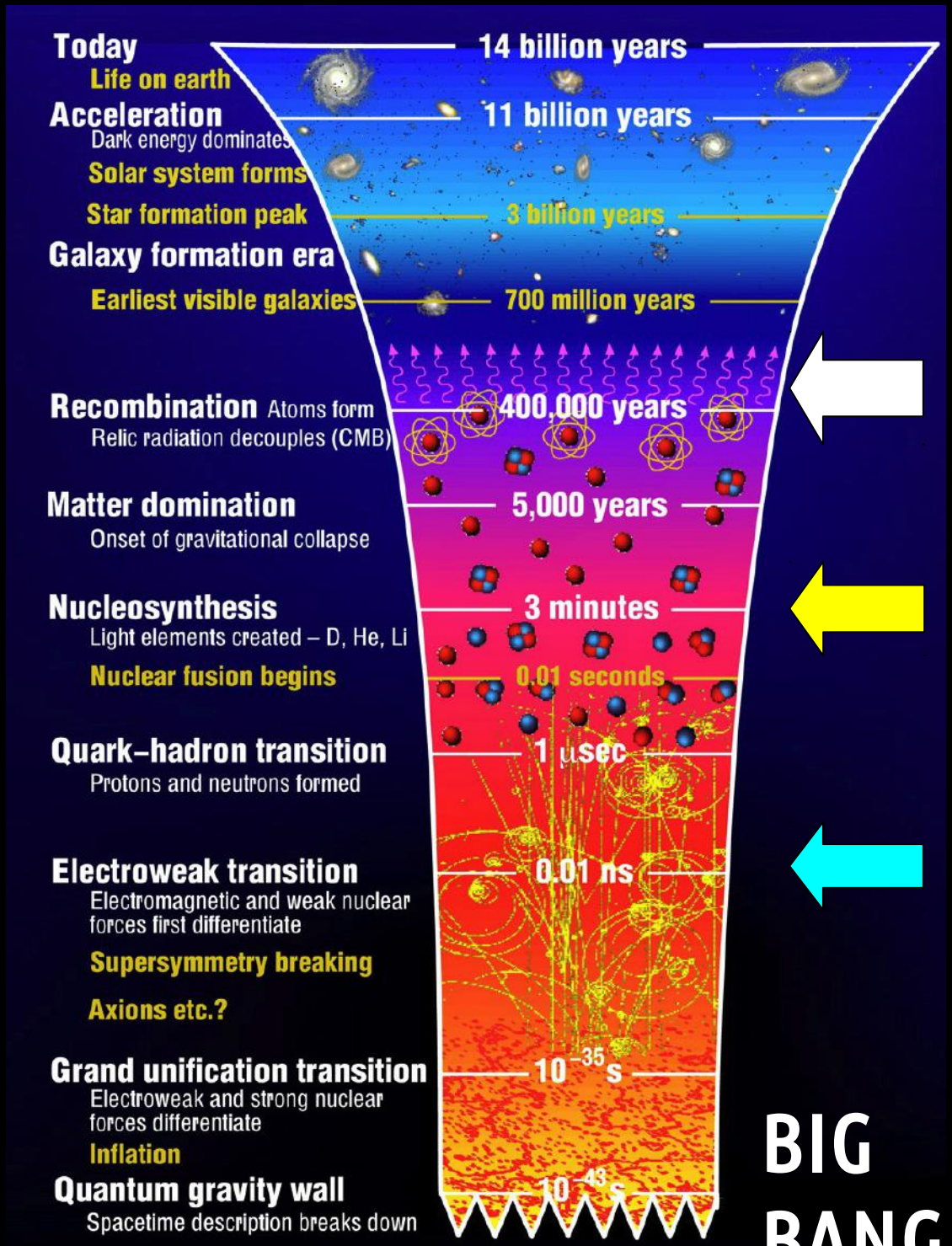


Neutrinos affect the CMB and large scale structure in the Universe …

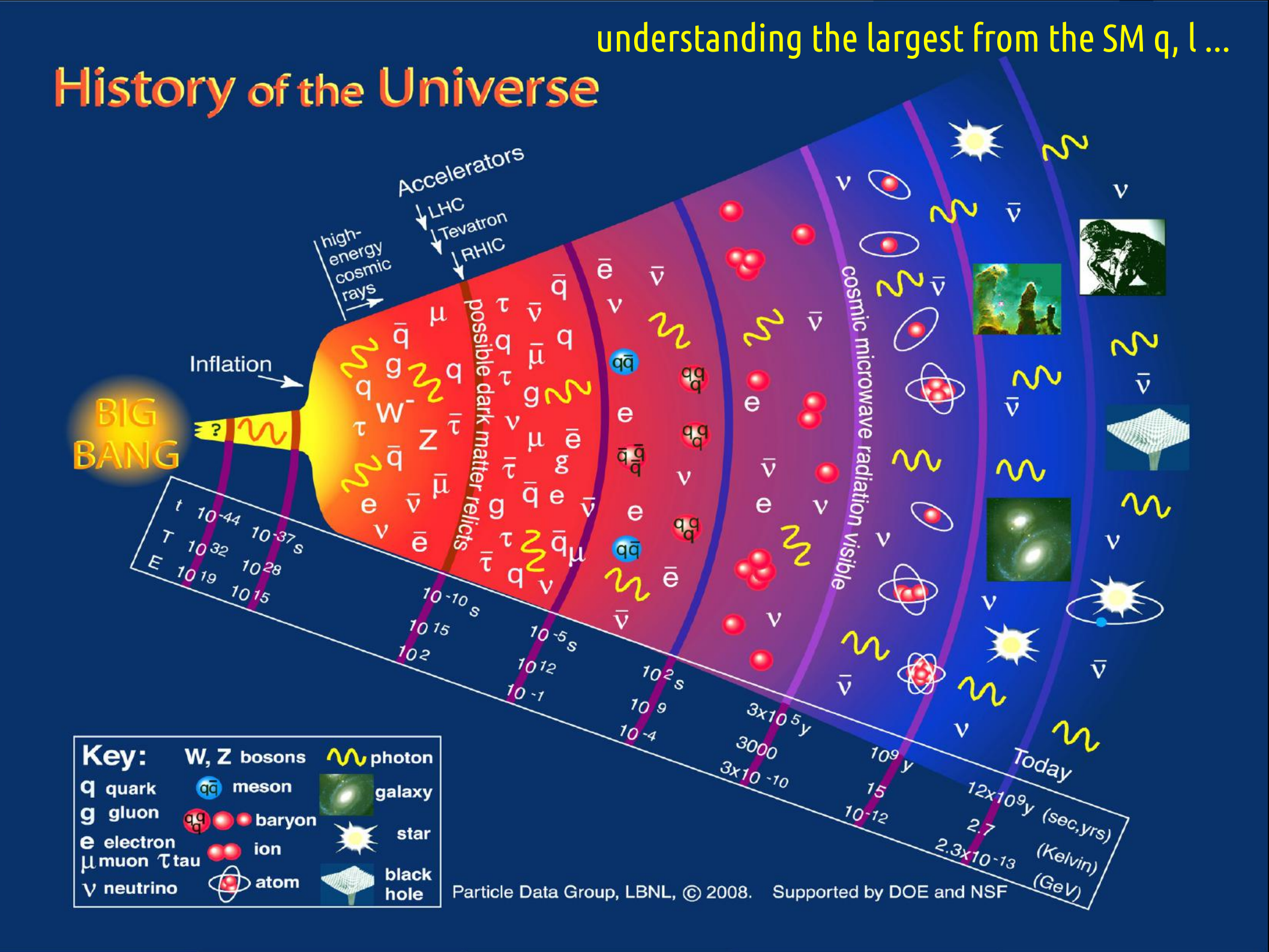
are key in the synthesis of light elements

can "probe" the Universe earlier than photons …

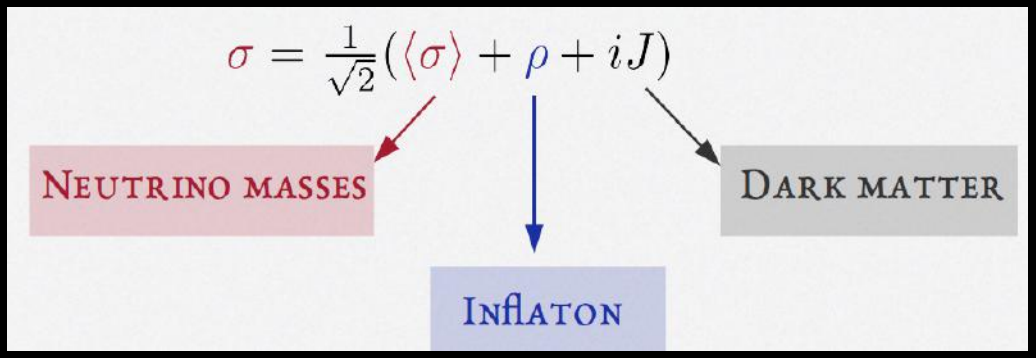




understanding the largest from the SM q, l ...



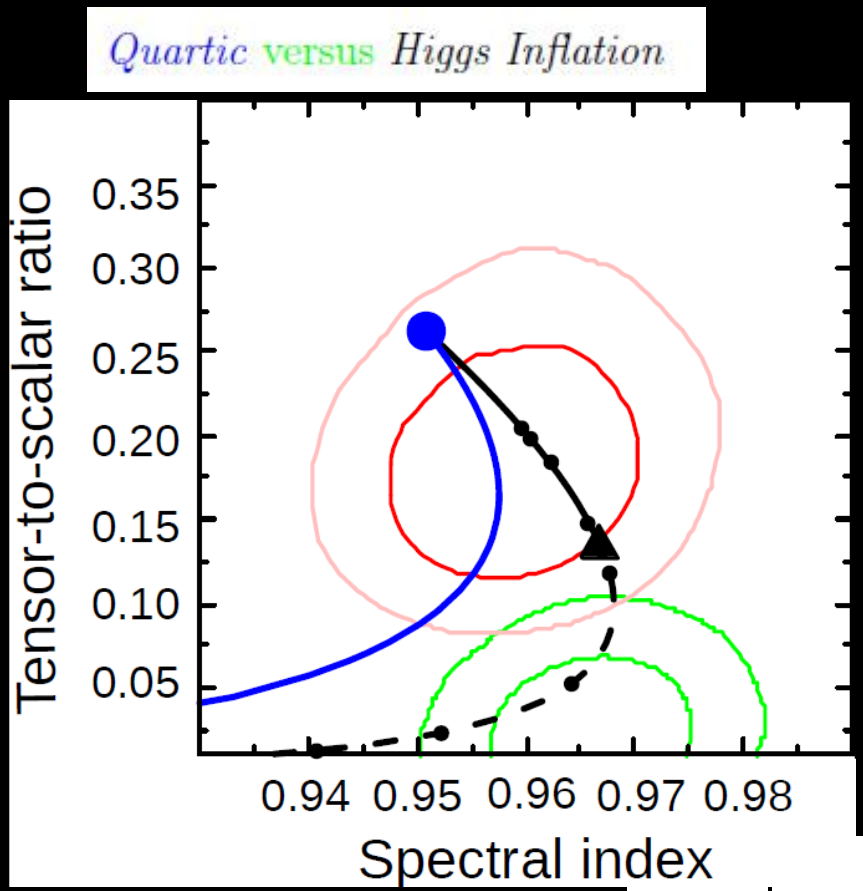
Seesaw inflation & majoron dark matter

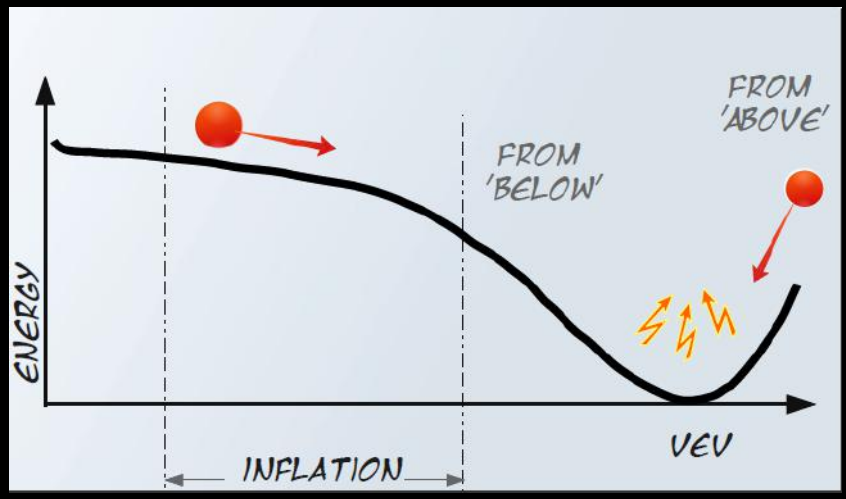


Boucenna et al arXiv:1405.2332 PRD90 (2014) 05502

type-I seesaw Leptogenesis

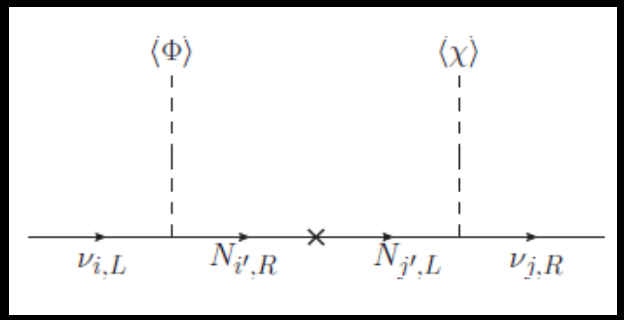
Aristizabal et al arXiv:1405.4706

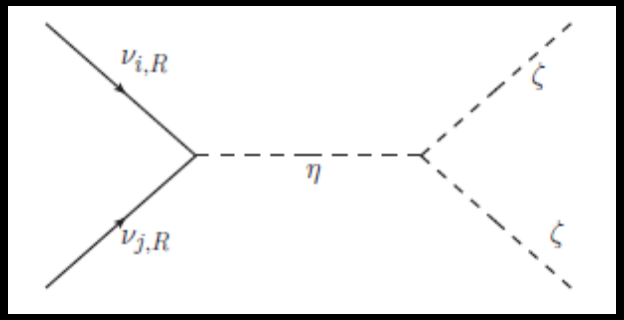


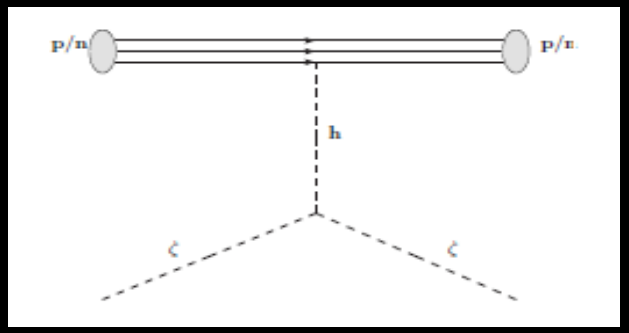


http://arxiv.org/pdf/1502.00612v1

Dark Matter Stability from Dirac nature of neutrinos



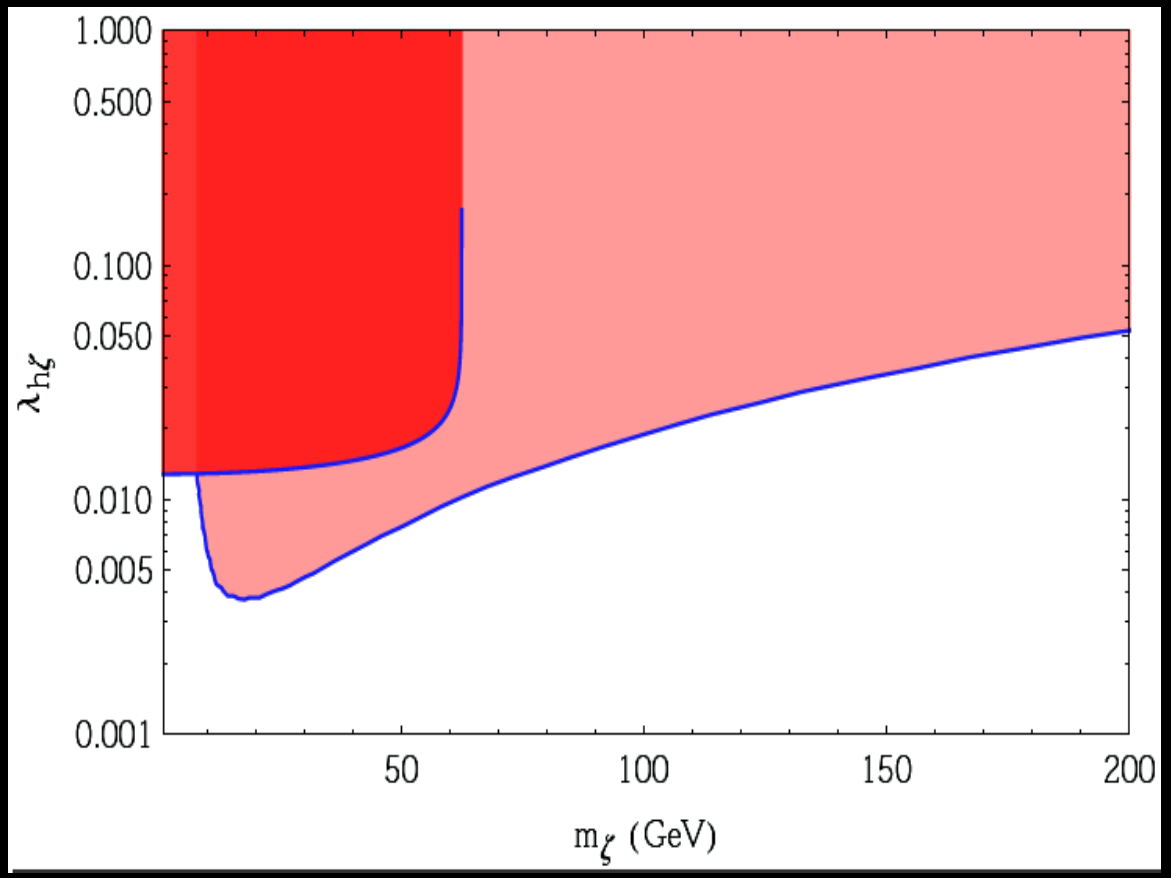




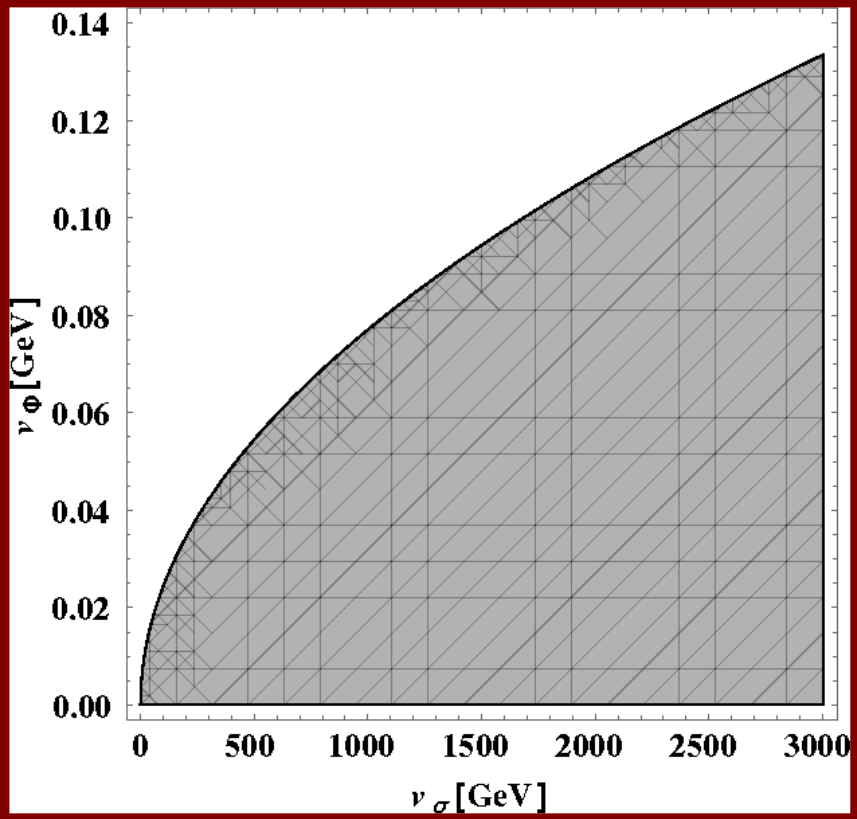
arXiv:1606.04543

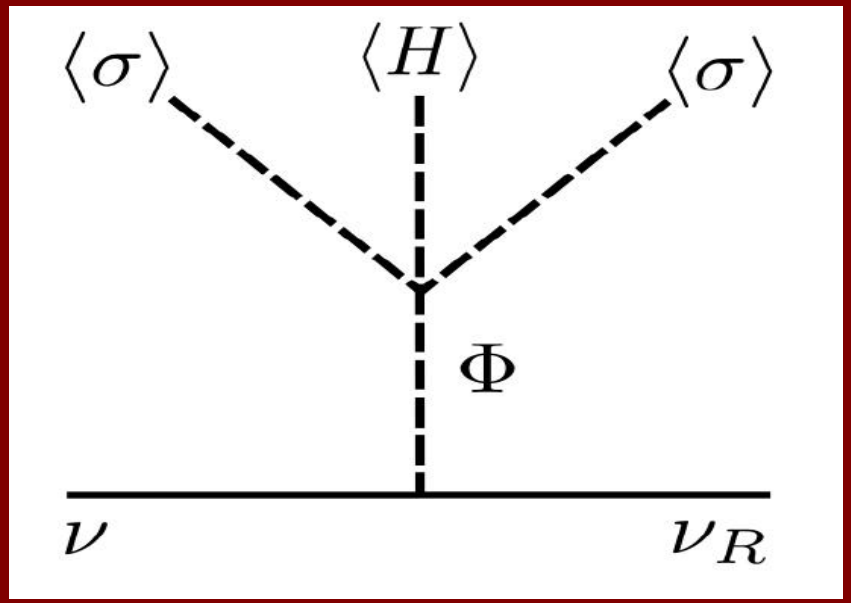
arXiv:1606.06904

Lepton Quarticity versus Lepton number



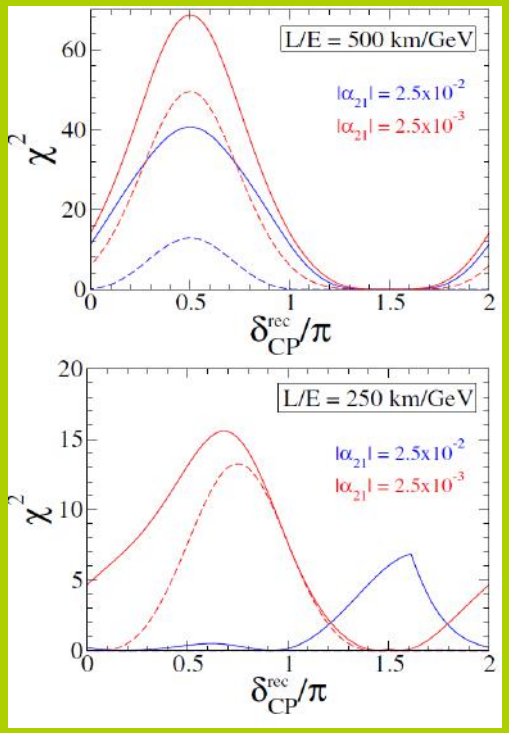
Diracon type-II seesaw

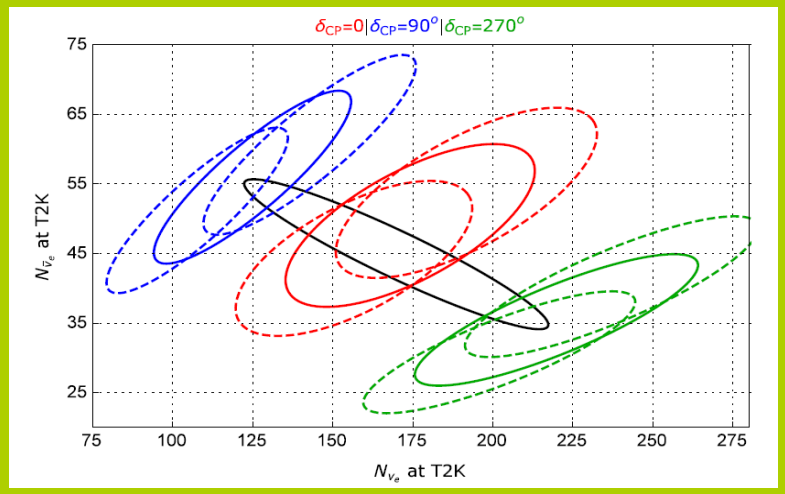




arXiv:1605.08362

Non unitary lepton mixing & CP





Schechter & JV PRD22 (1980) 2227 & PDG

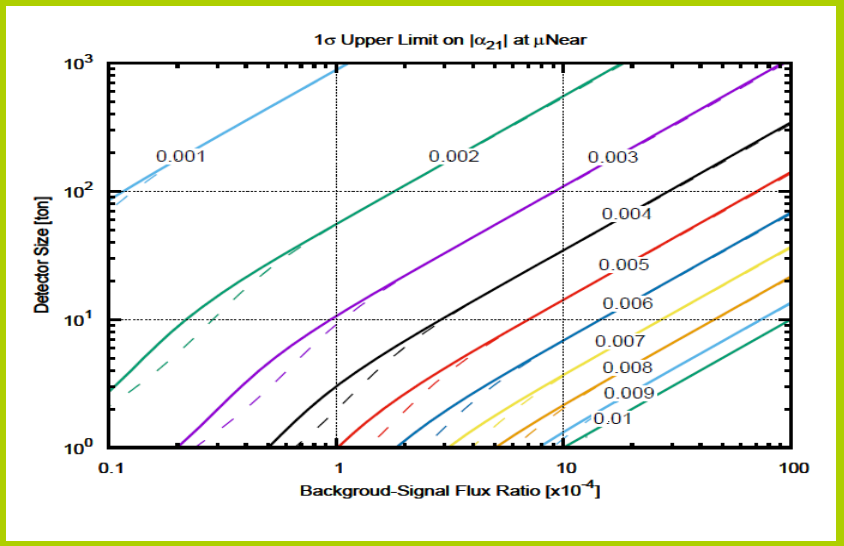
Rodejohann, JV Phys.Rev. D84 (2011) 073011

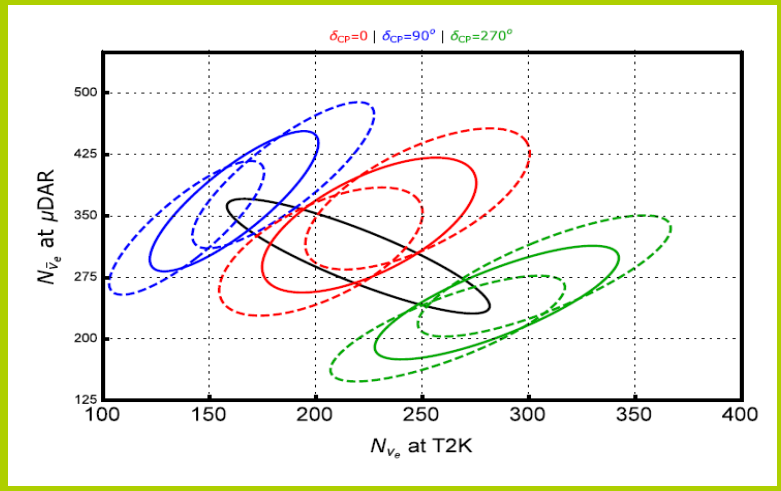
http://dx.doi.org/10.1103/PhysRevD.92.053009

arXiv:1604.05690

ArXiv:1605.01670

atm

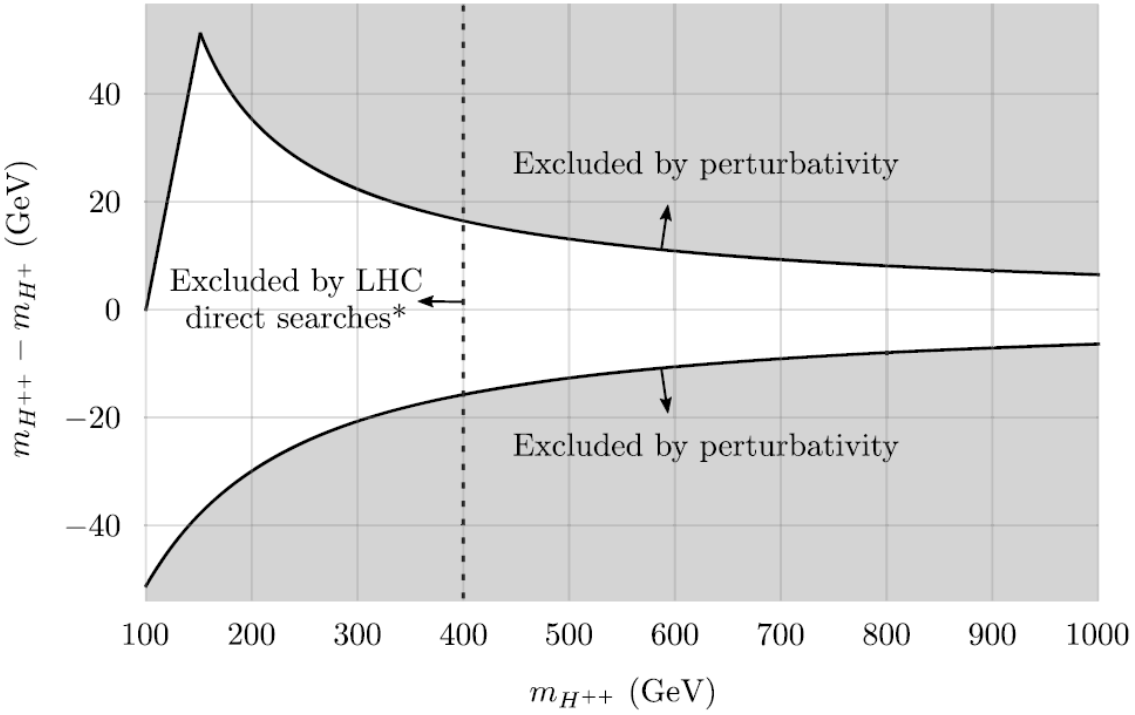


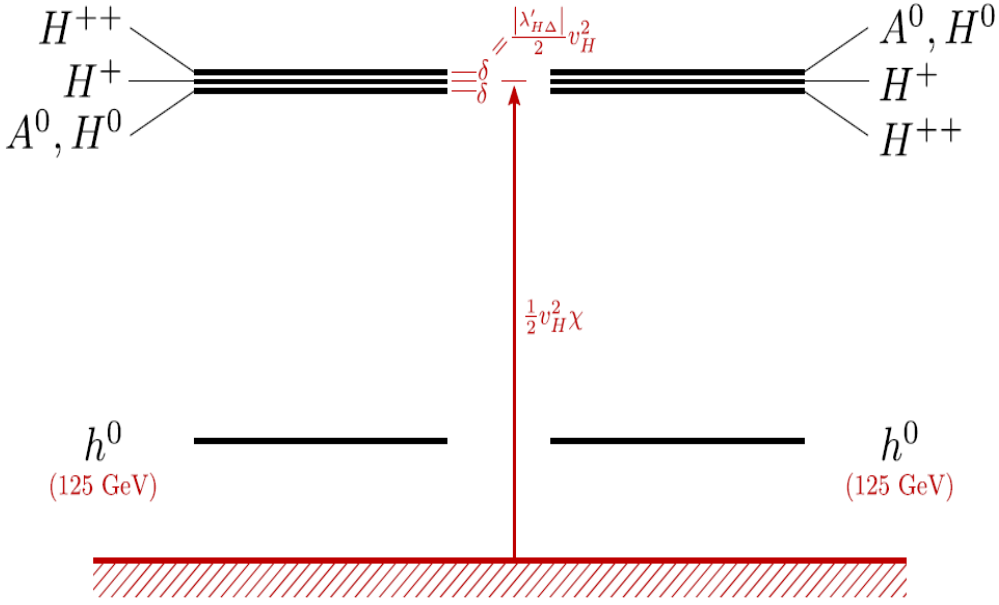


Valle

PHYSICAL REVIEW D **92,** 075028 (2015)

Consistency of the triplet seesaw model revisited

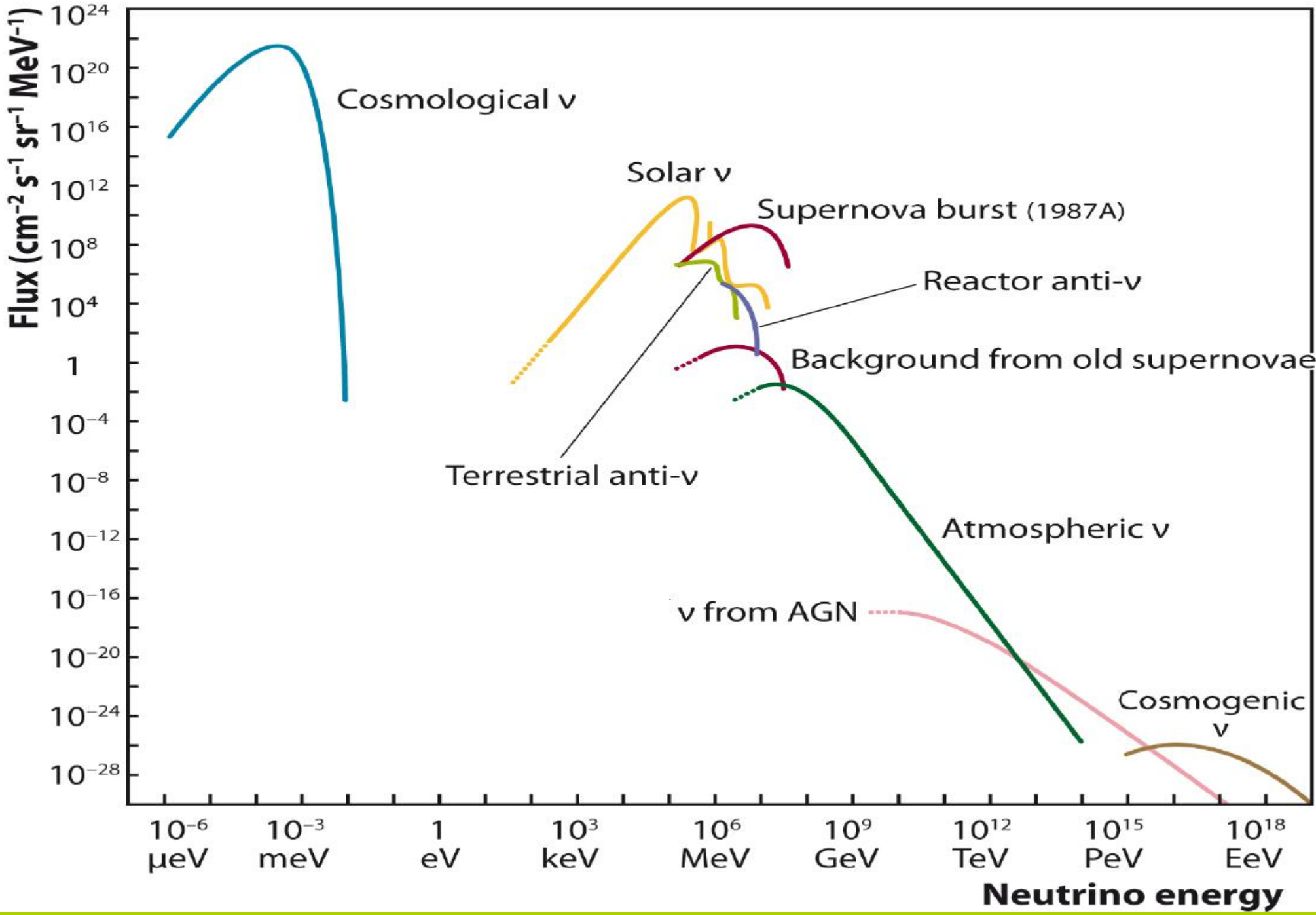
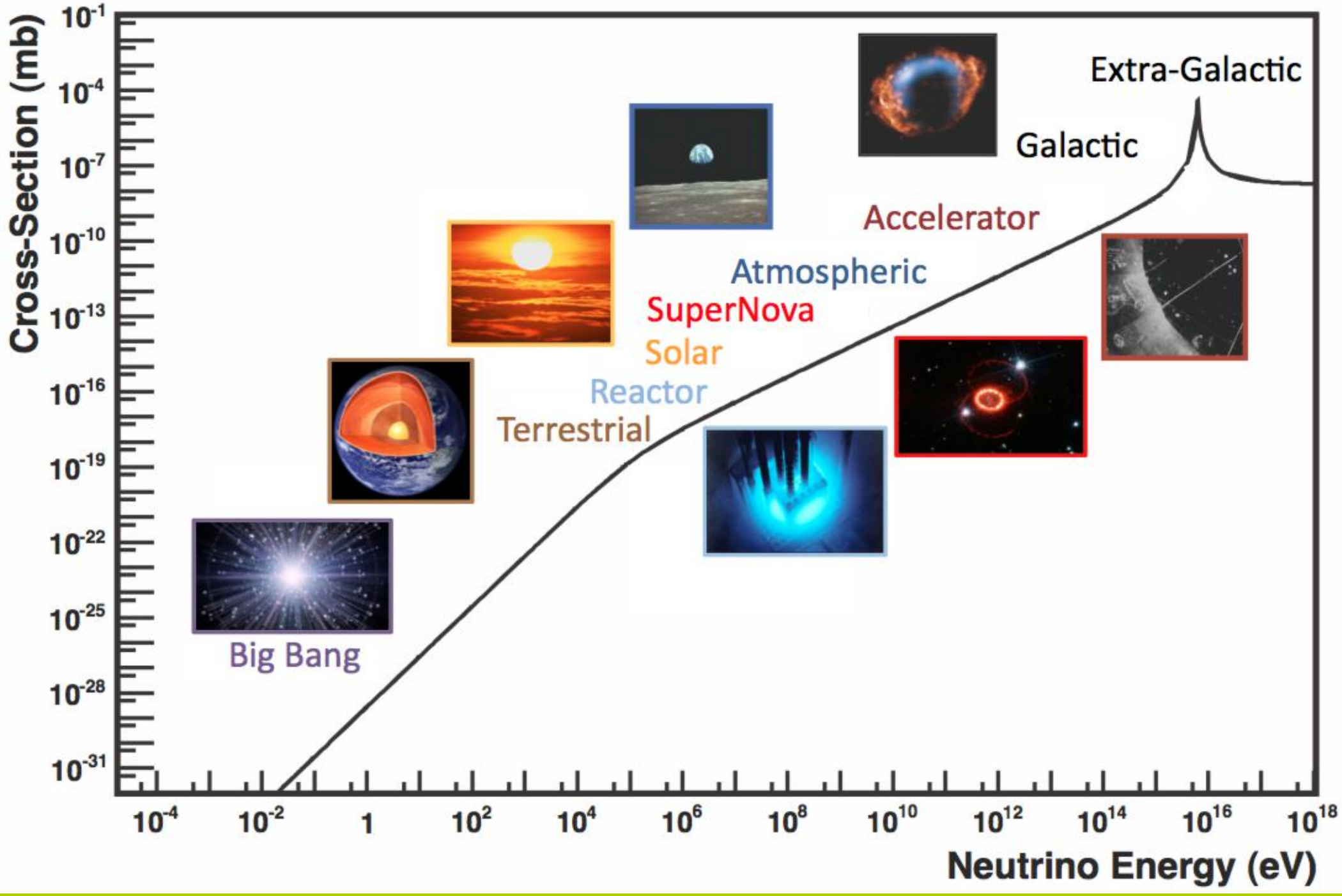




IOP Publishing *New J. Phys.* **18** (2016) 033033

Neutrino as higgs benchmark

neutrino sources



neutrino cross sections