Neutrino physics and implications

José W F Valle

Lecture I

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

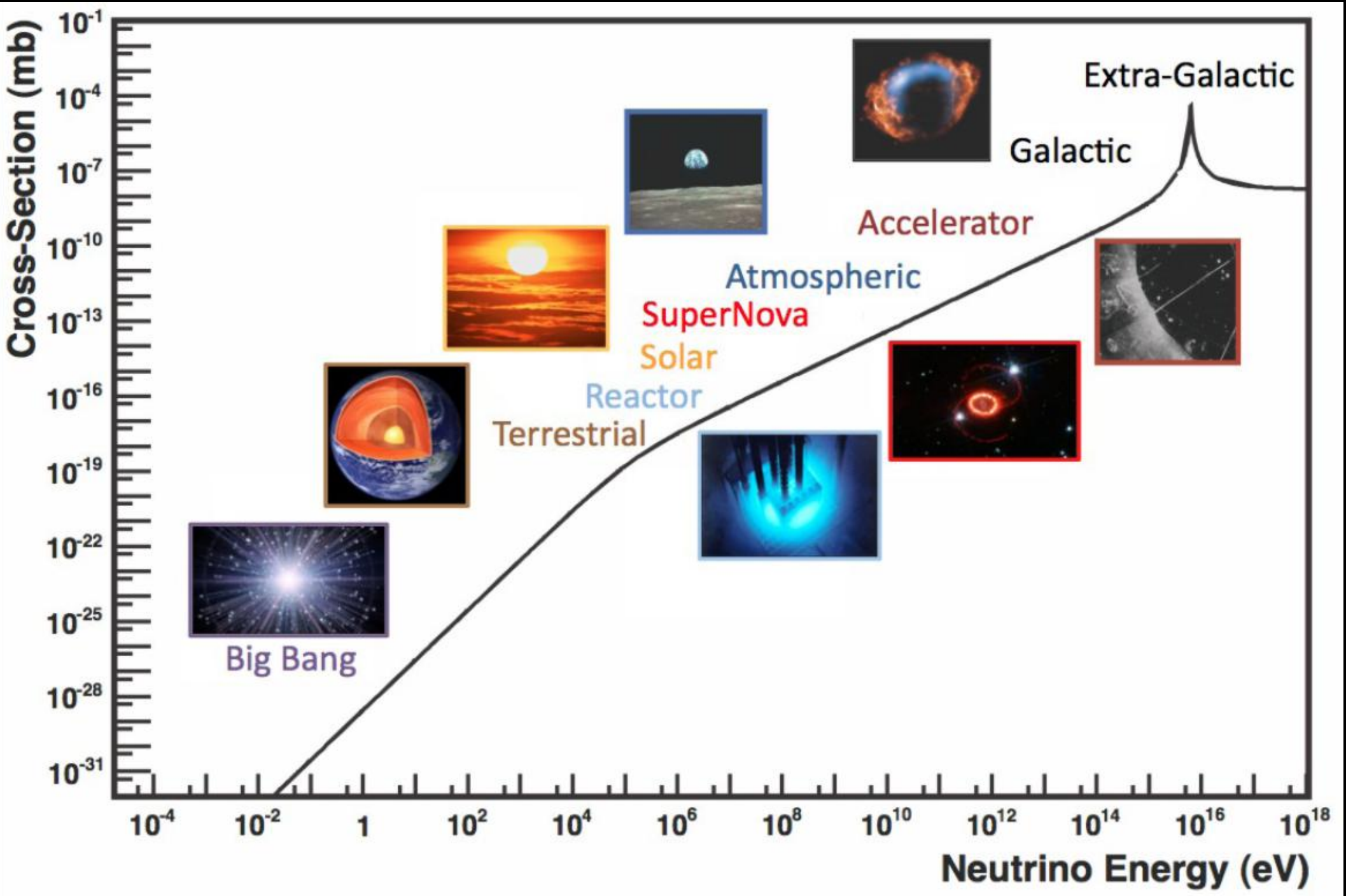
Summer School and Workshop on Standard Model and Beyond – Corfu 2016

Outline

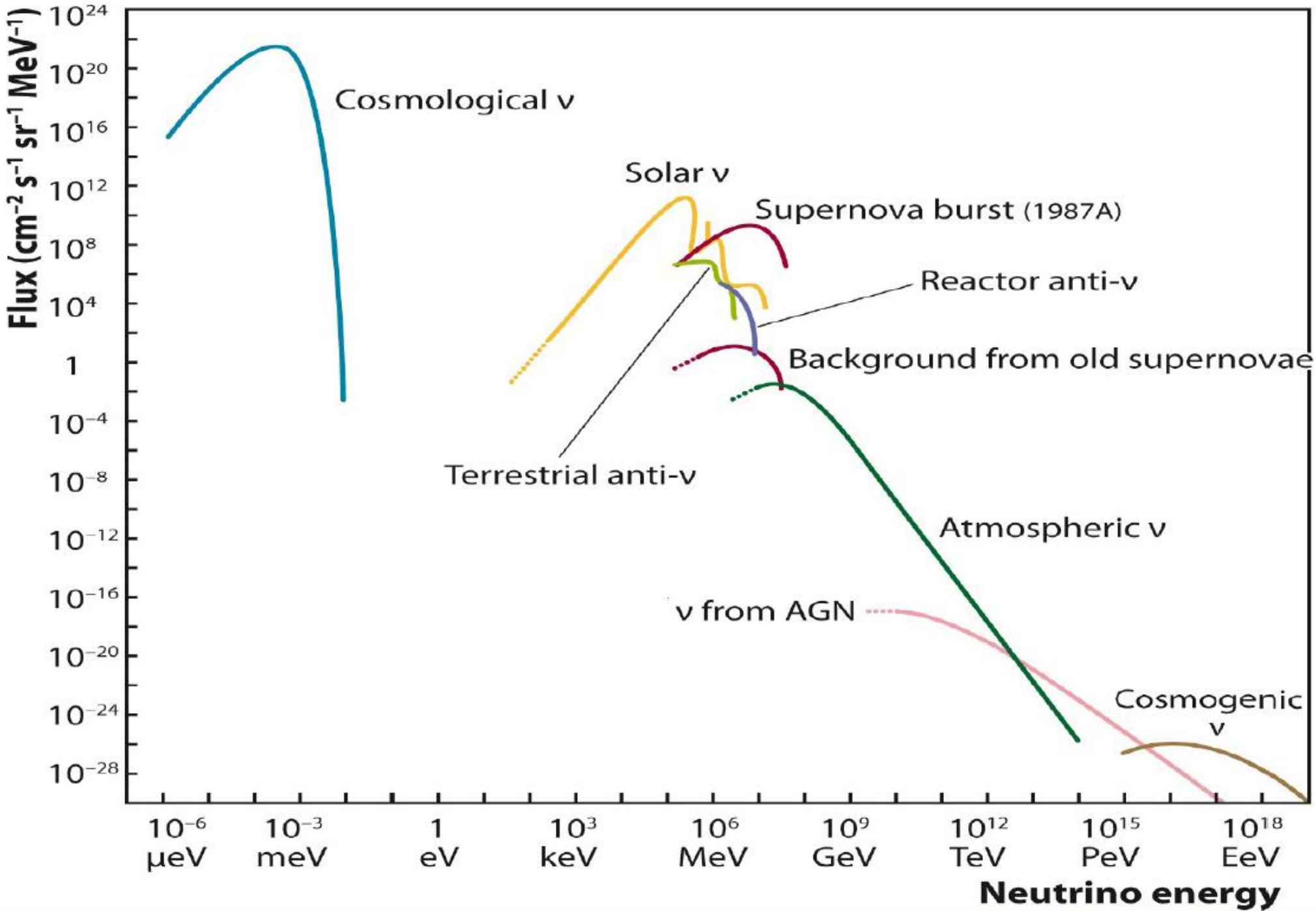
Lecture I

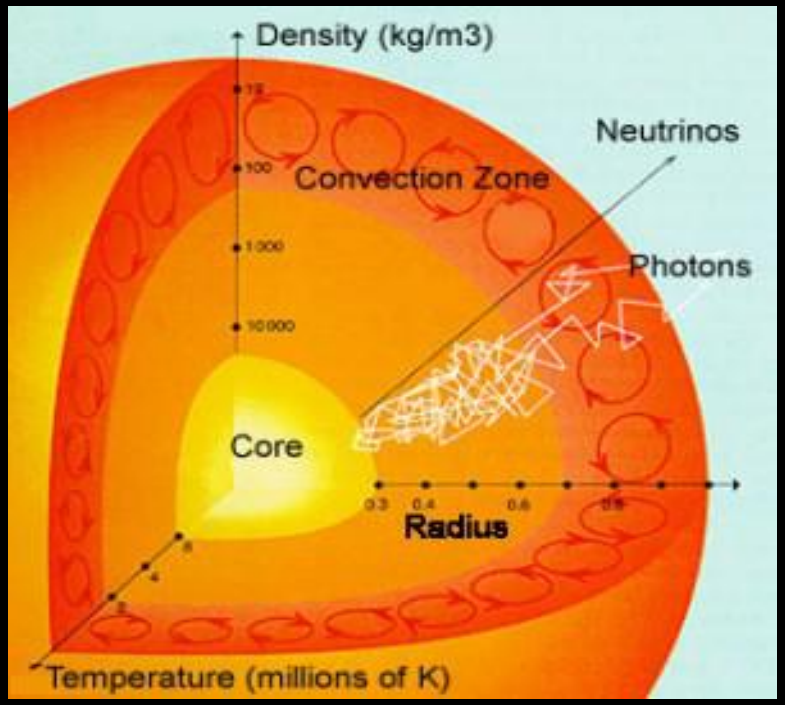
- Why neutrinos
- Neutrinos in the Standard model
- Neutrino oscillations
- Origin of neutrino mass
- Seesaw mechanisms
- Radiative mechanisms
- SU(3)c⊗SU(3)L⊗U(1) electroweak model
- The flavor problem
- Symmetry approaches
- The role of neutrinos
- Neutrinos and unification

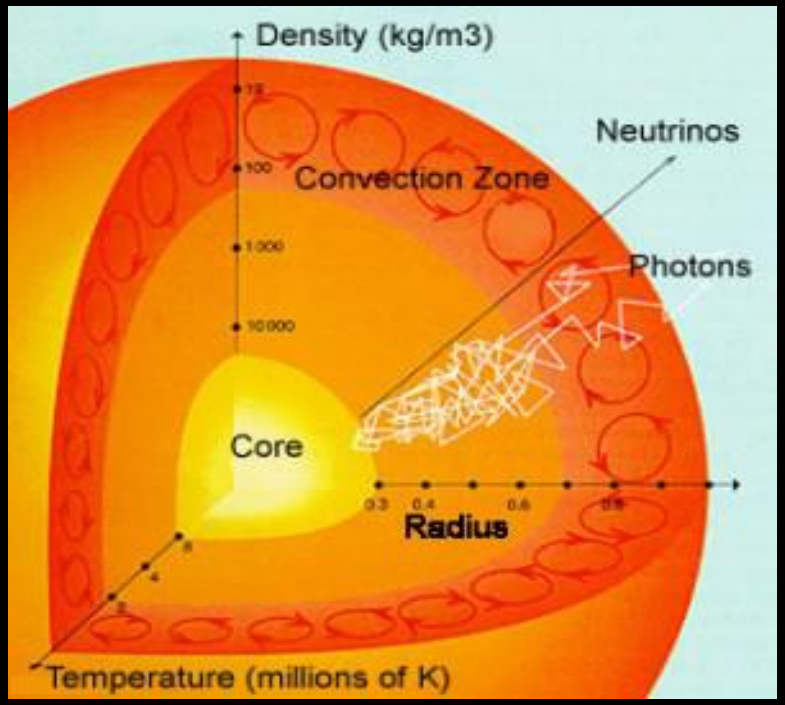
neutrino cross sections



neutrino sources




Density (kg/m3)
100
1 000
10 000
Neutrinos
Convection Zone
Photons
Core
0.3
0.4
0.6
0.8
Radius
Temperature (millions of K)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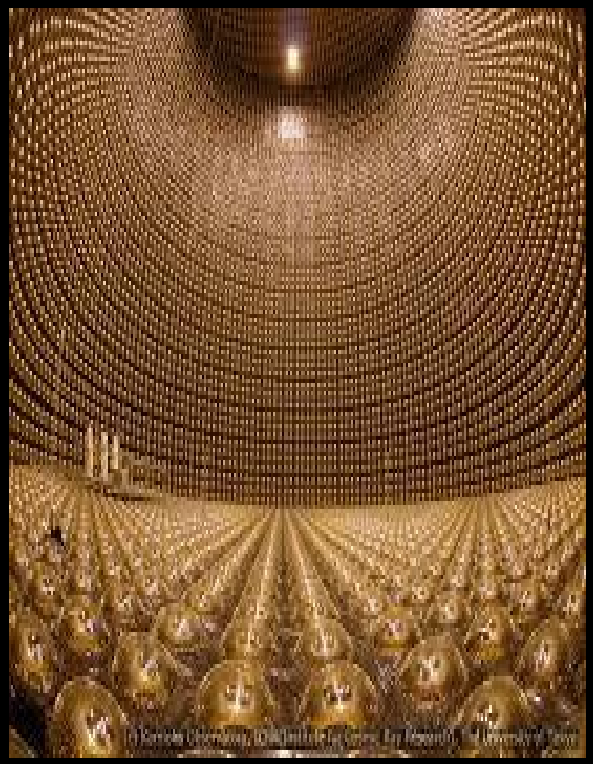

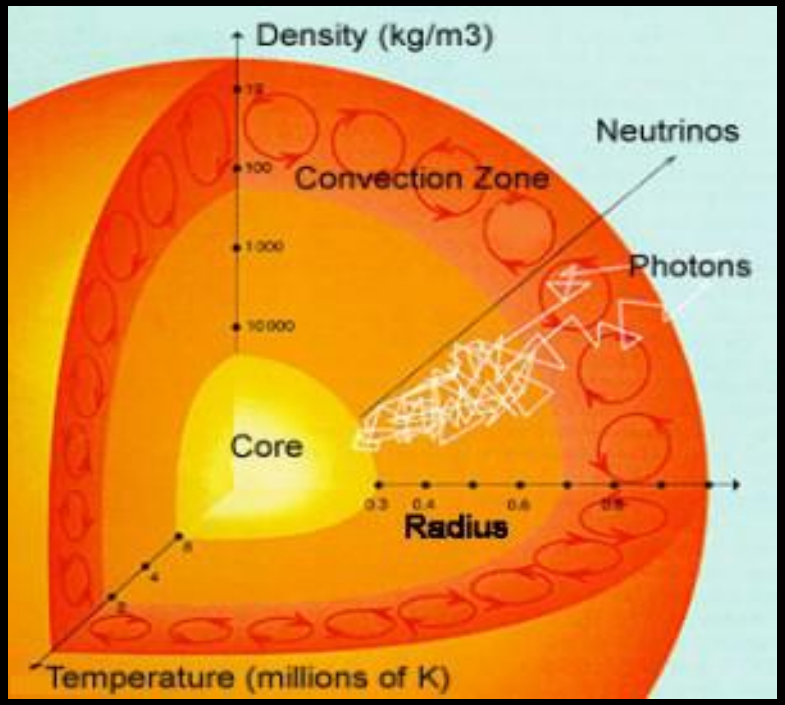
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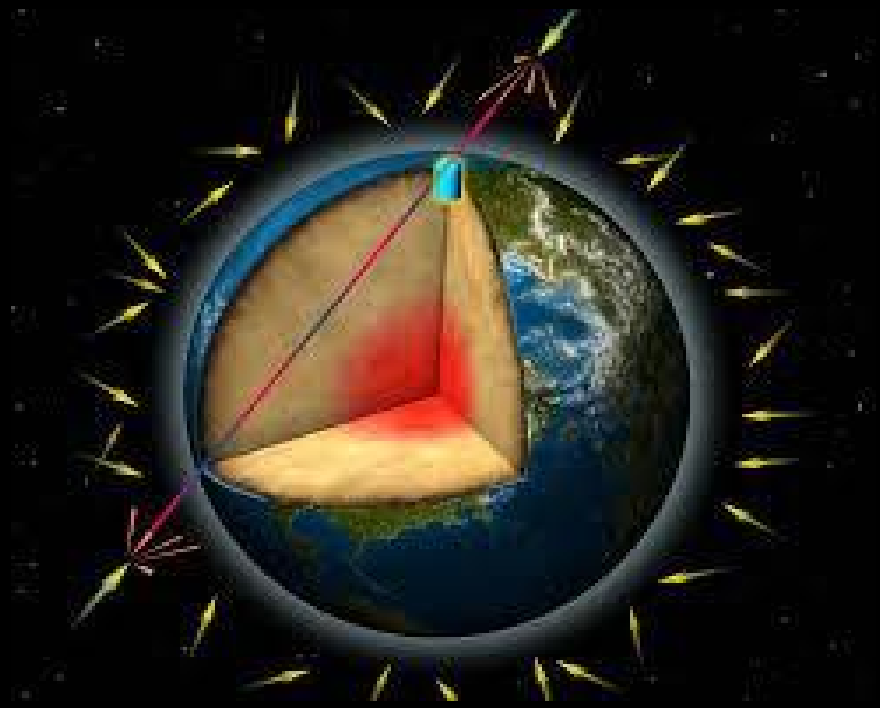

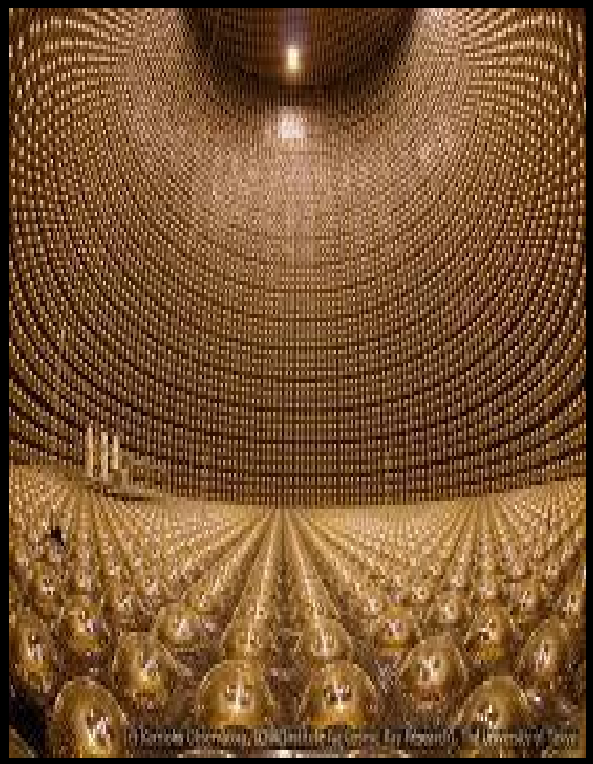

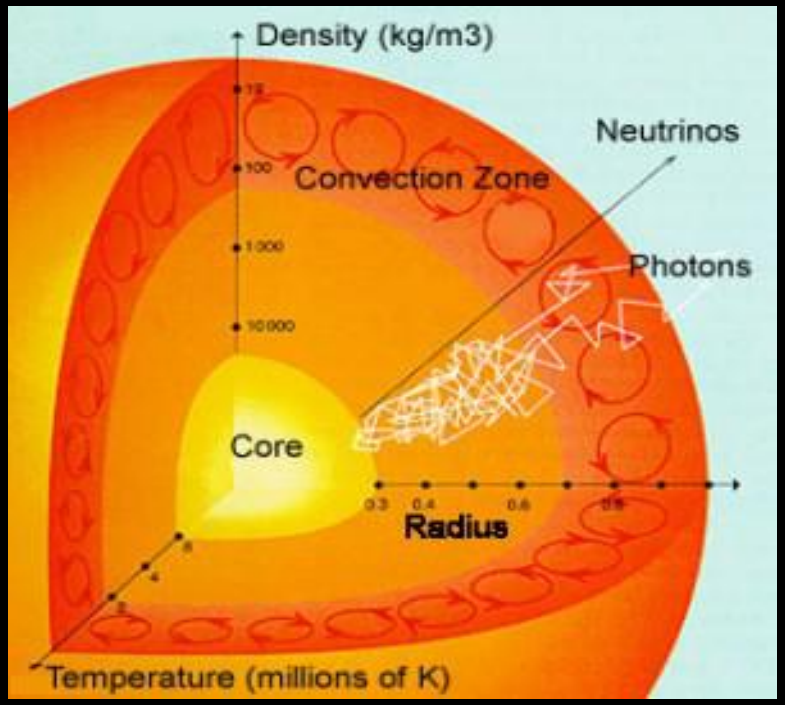
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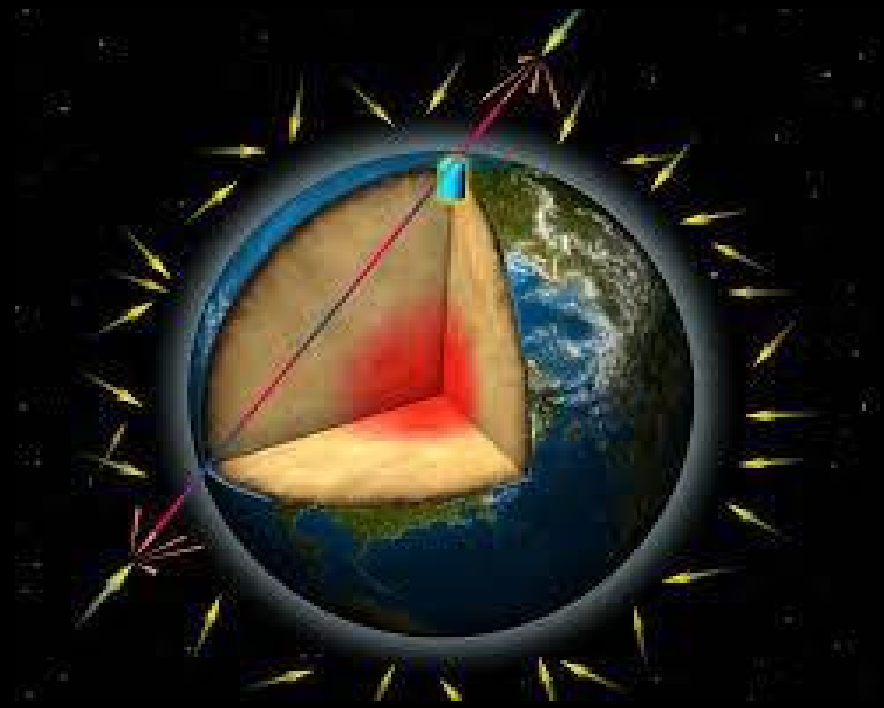
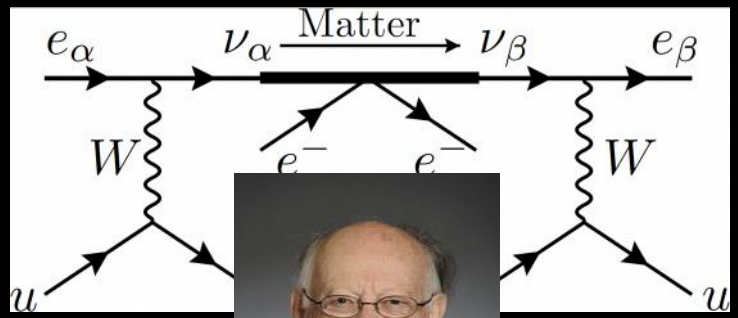
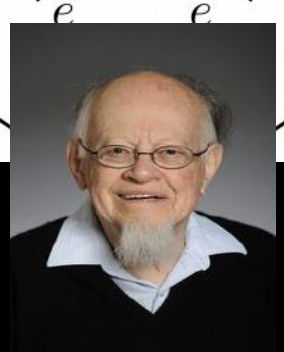
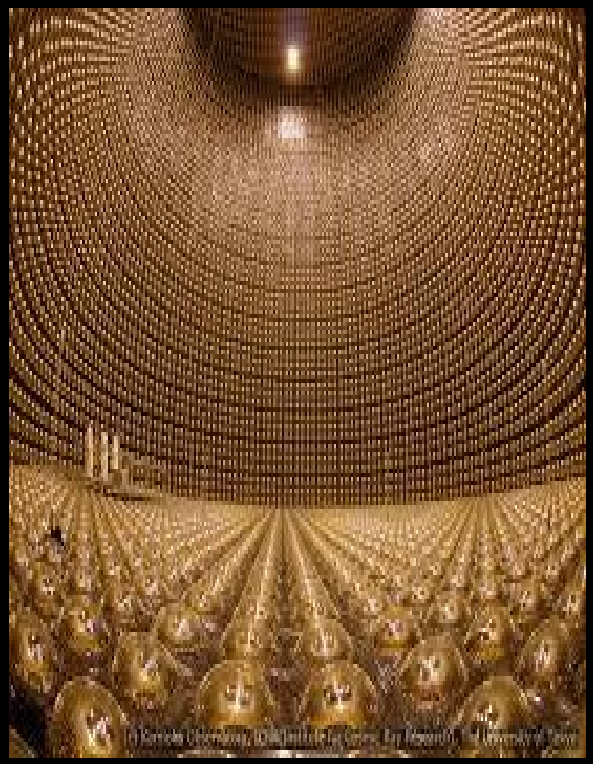
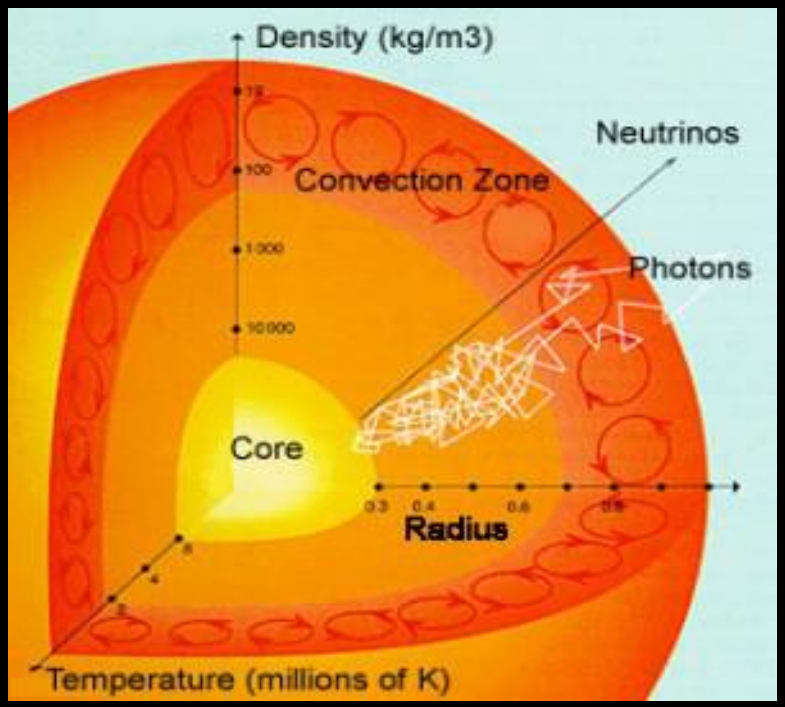



e_α
ν_α
Matter
ν_β
e_β
W
e^-
e^-
W
u
u



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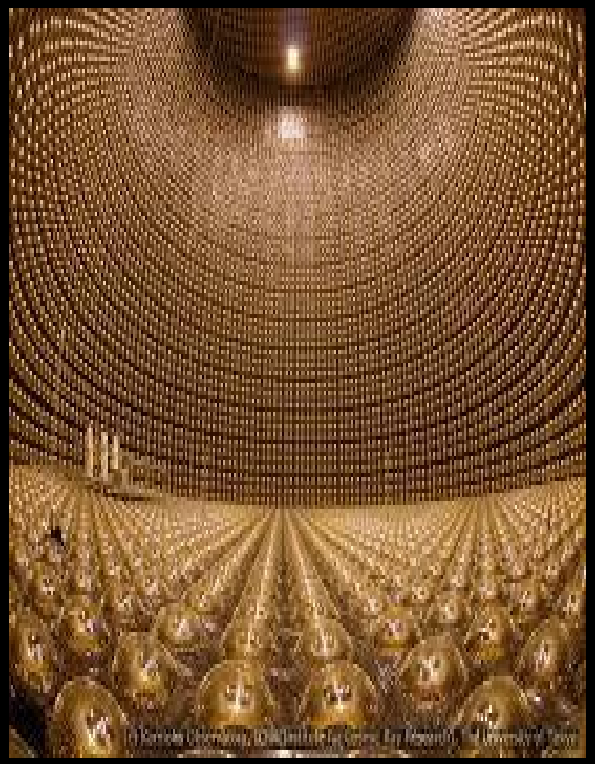
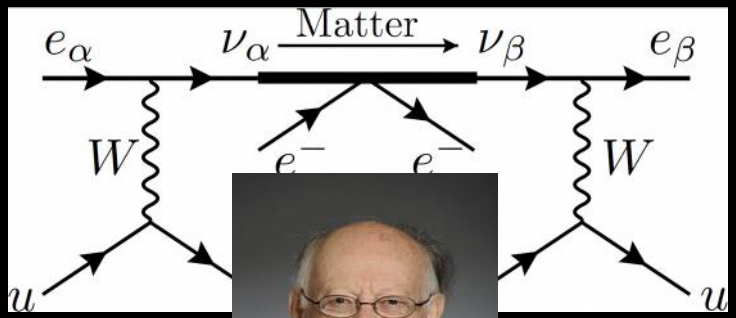
Neutrinos
Convection Zone
Photons
Core
Radius
Temperature (millions of K)


ALFR.
NOBEL

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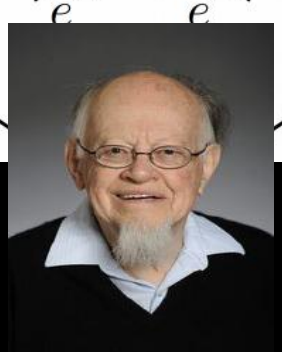
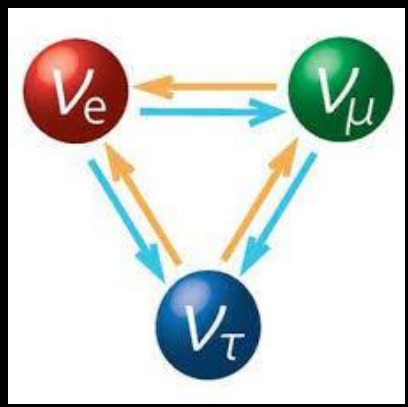
ν_α
Matter
ν_β
e_β
W
e^-
e^-
W
u
u




ν_e
ν_μ
ν_τ

Why the fuss about neutrinos

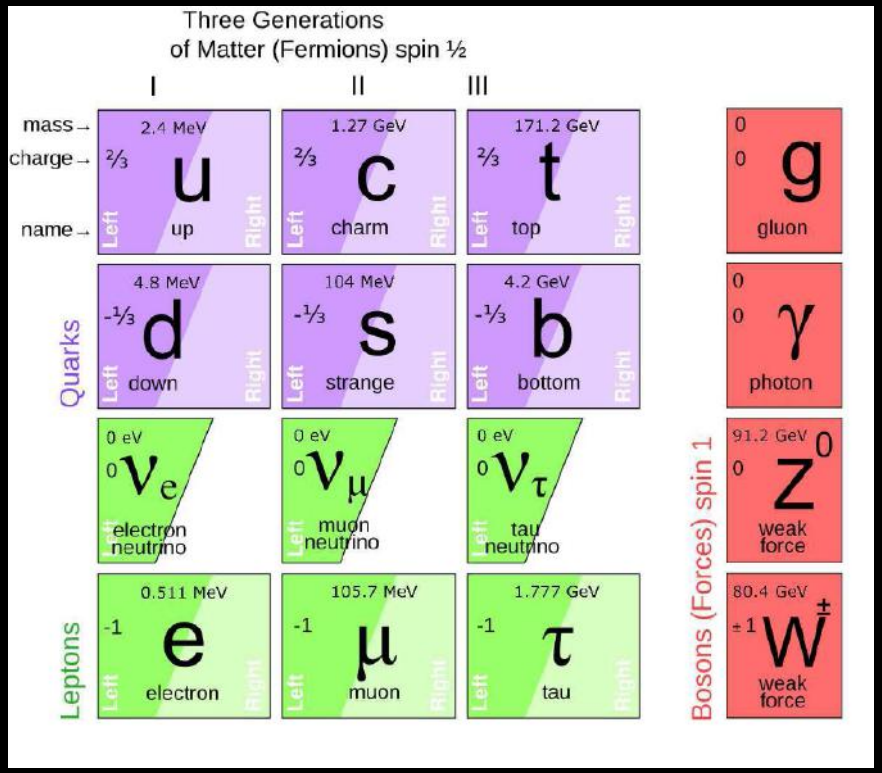
Can not do without neutrinos

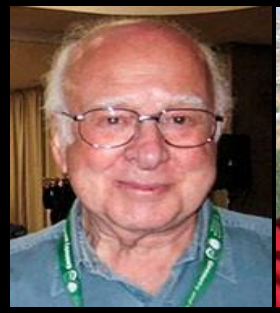
Basic cosmogical and astro probe

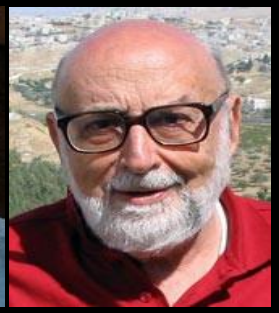
key building block of the Standard Model

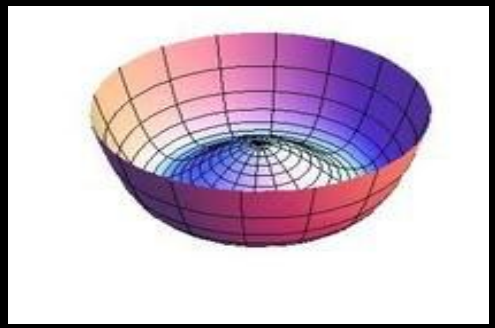
Standard model

$$\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$$





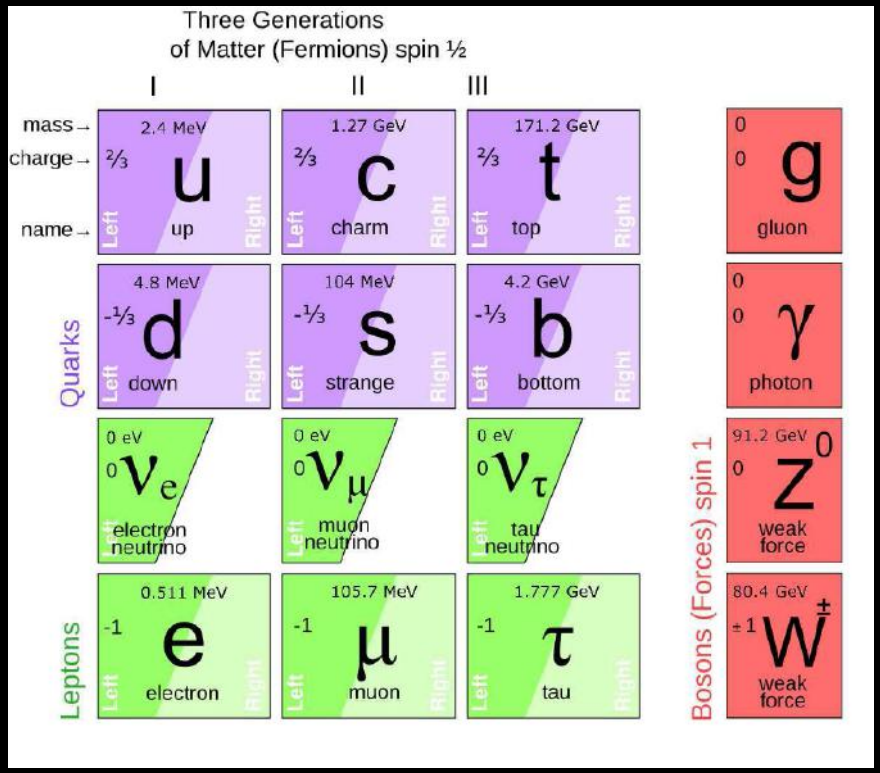


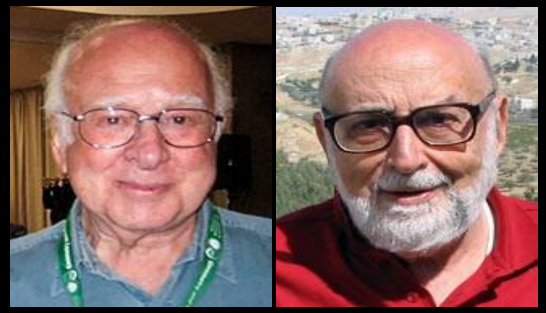


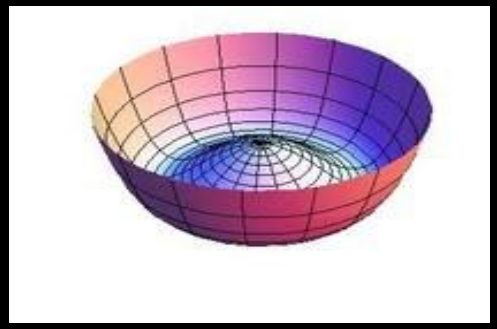
Standard model

$$\mathrm{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y}$$

125 GeV
0
0
H
Higgs boson
spin 0







Standard model

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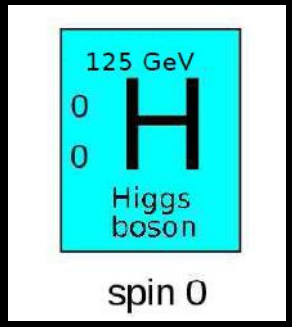
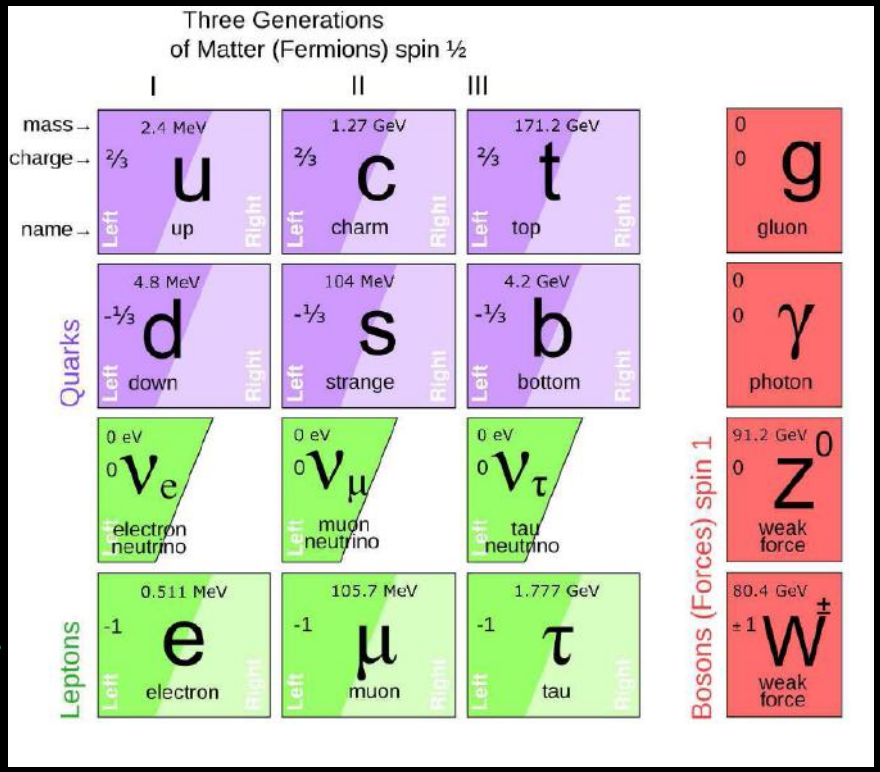
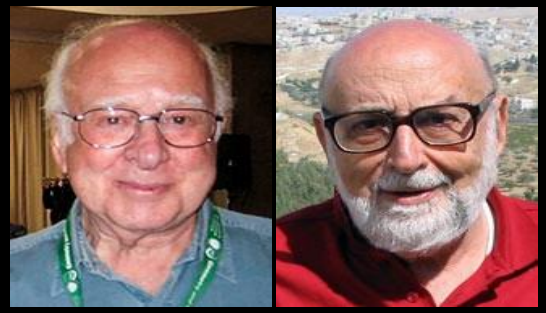
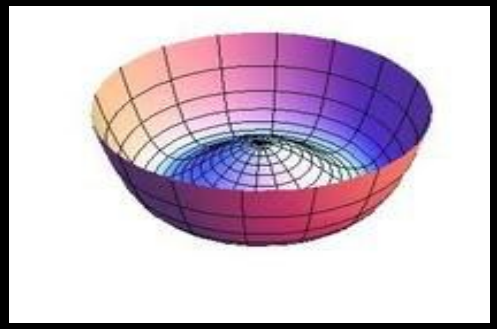


Last brick ? ...







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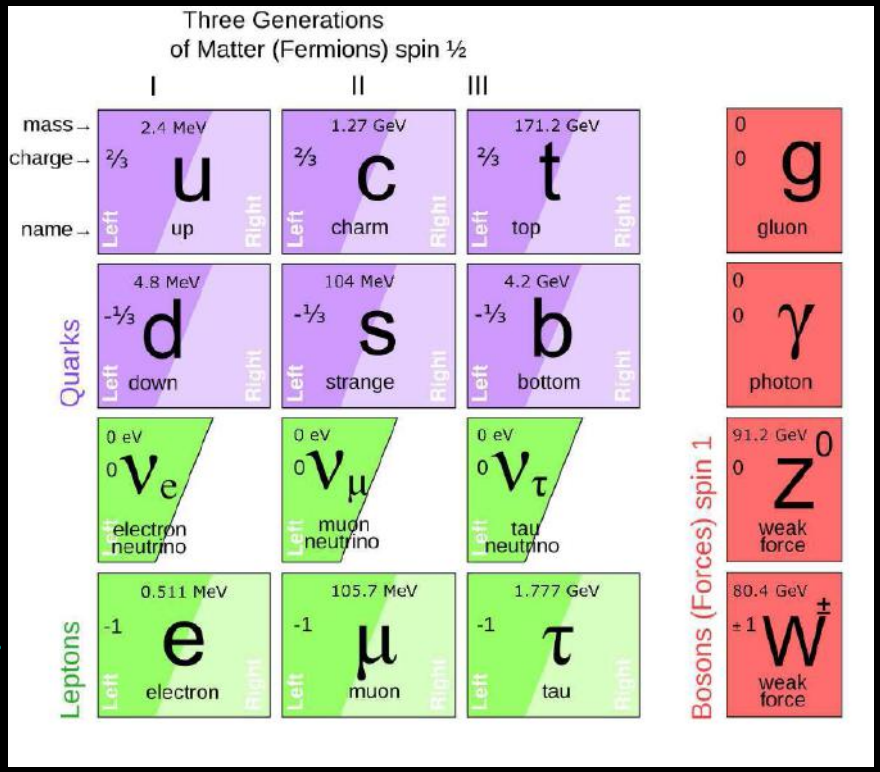

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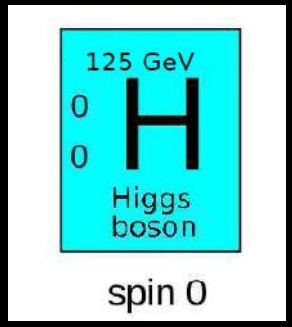

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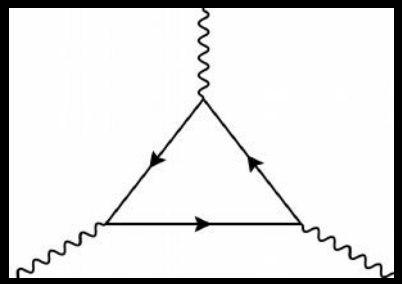
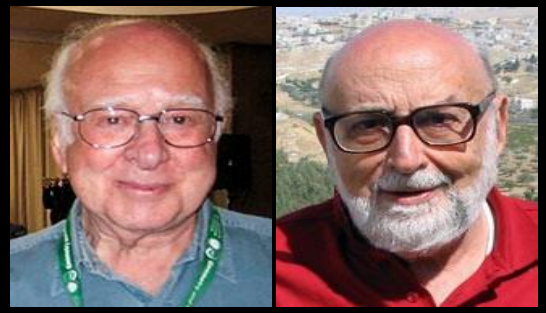
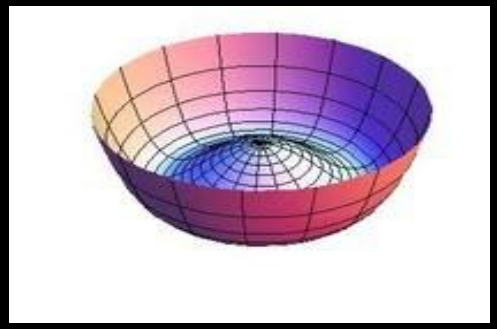
anomalies



Charge quantization





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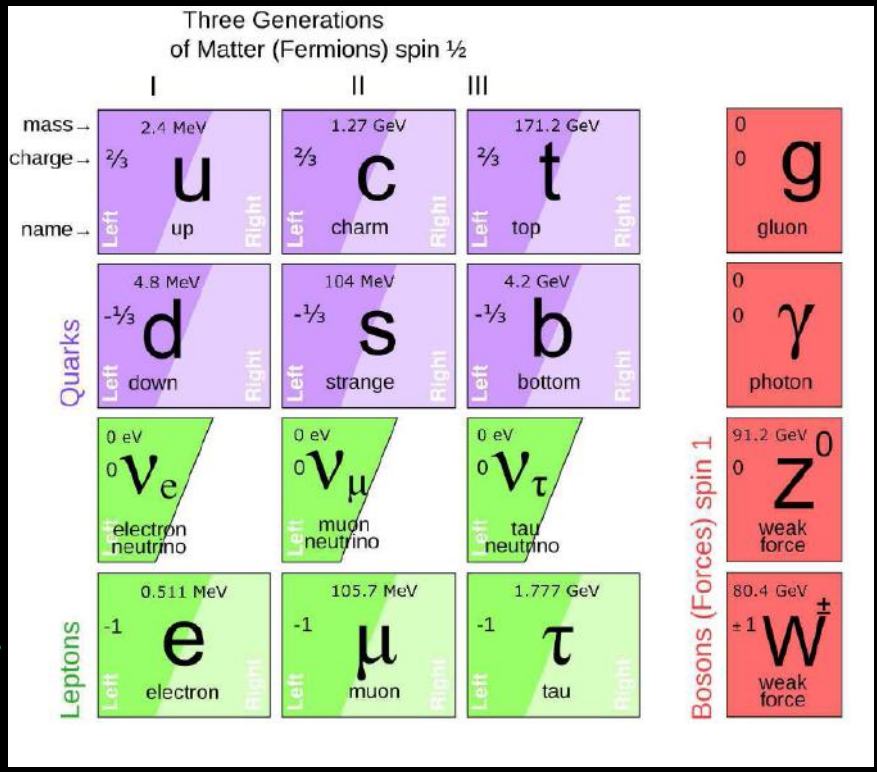

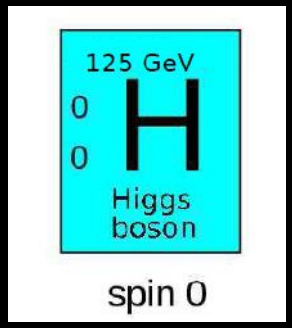

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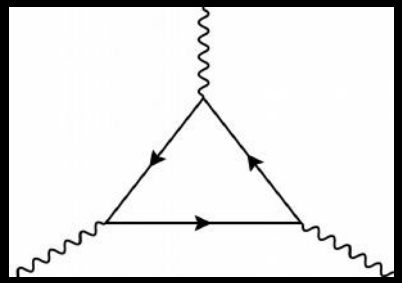

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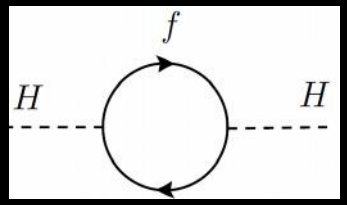
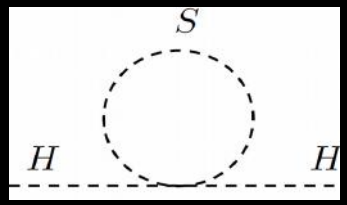
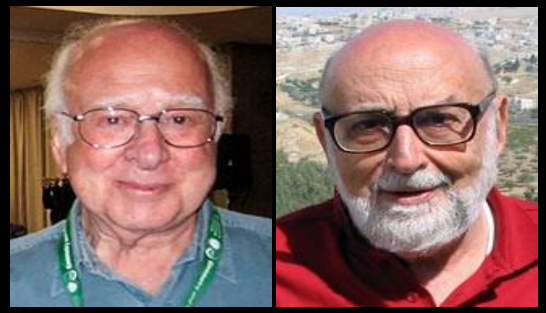
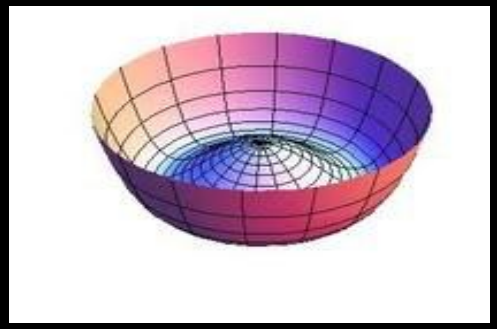
Consistency of SSB









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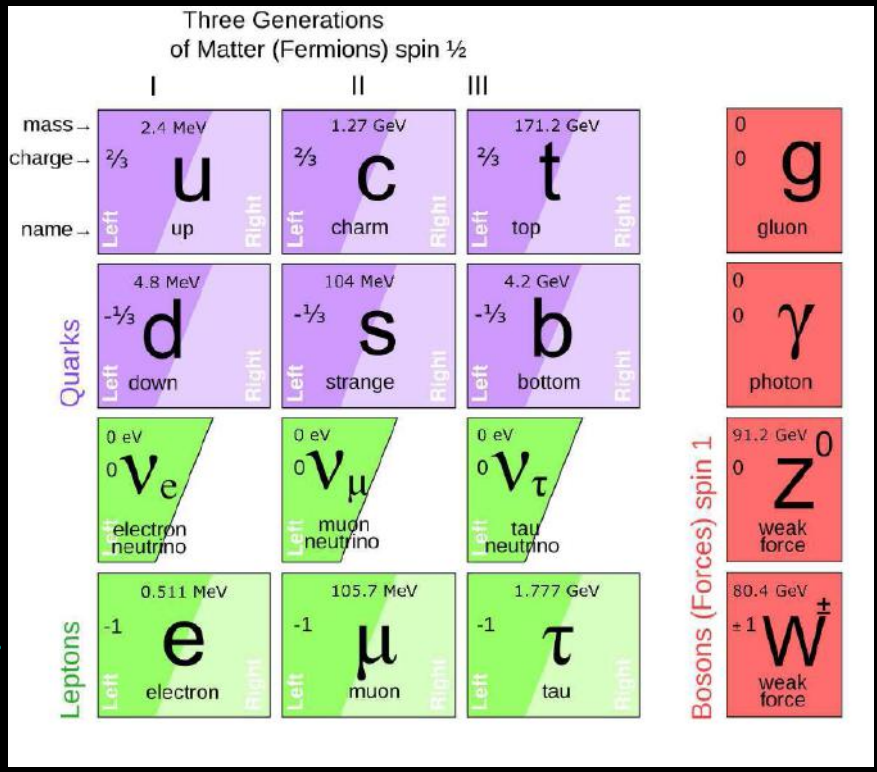

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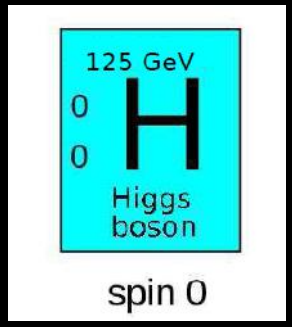

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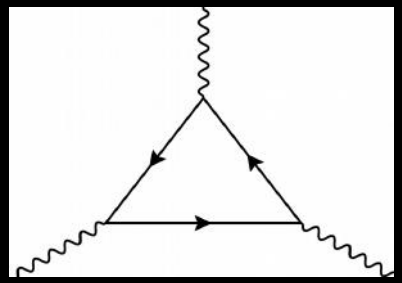
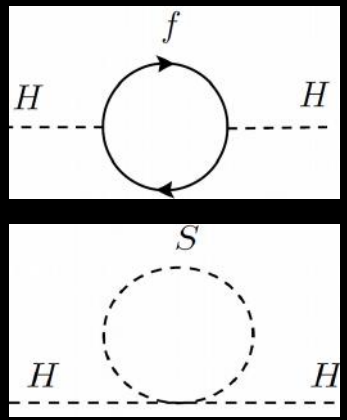
anomalies

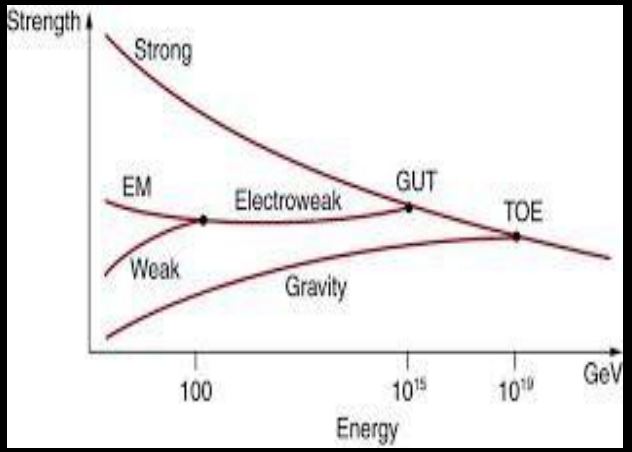


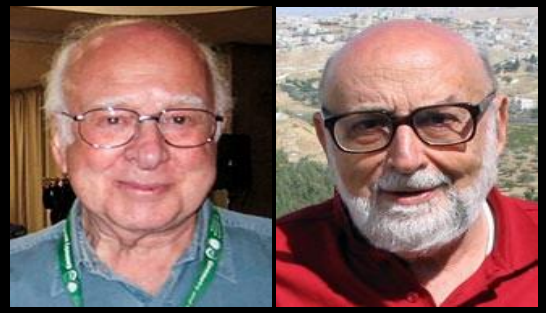
Charge quantization

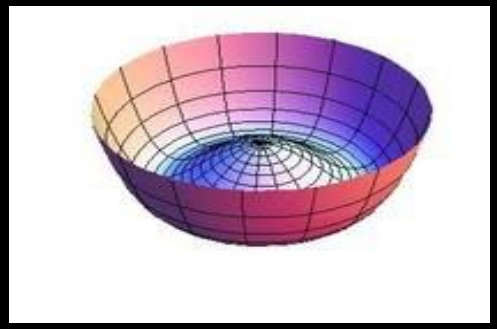
Consistency of SSB



coupling unification







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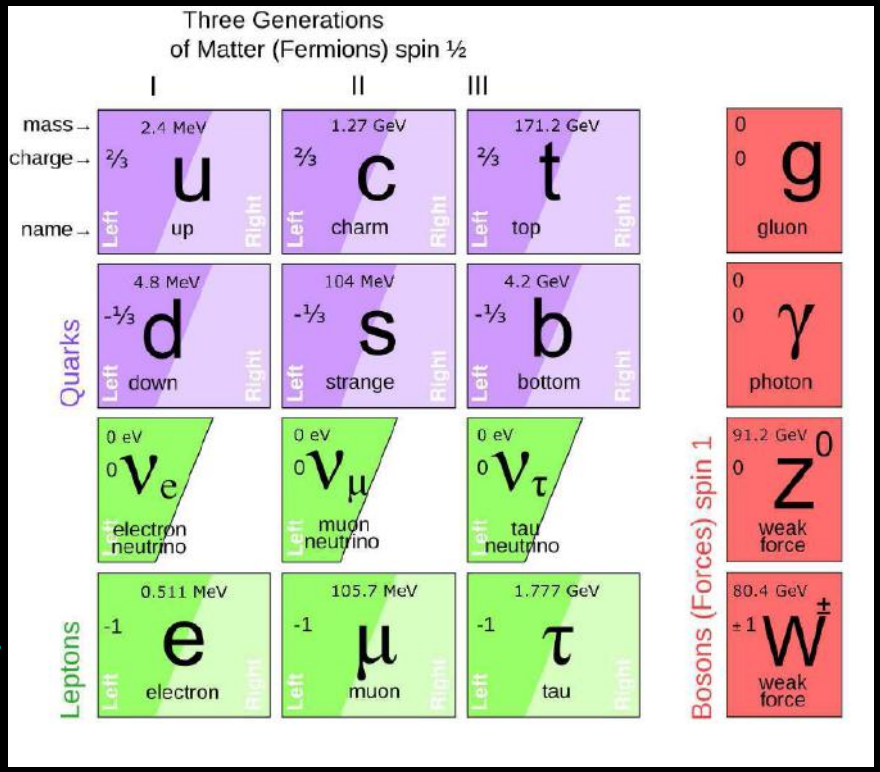

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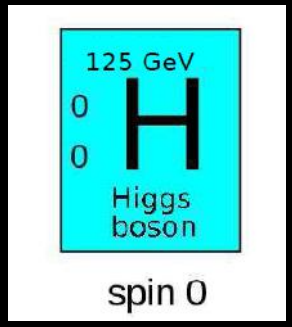

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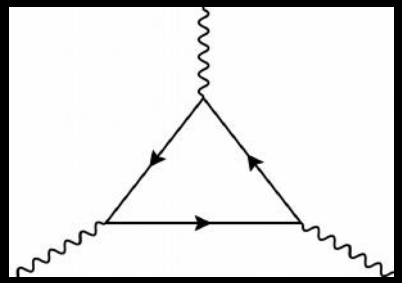
anomalies



Charge quantization

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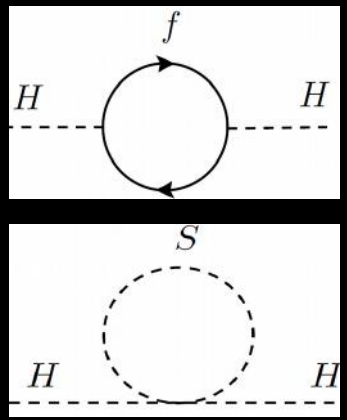
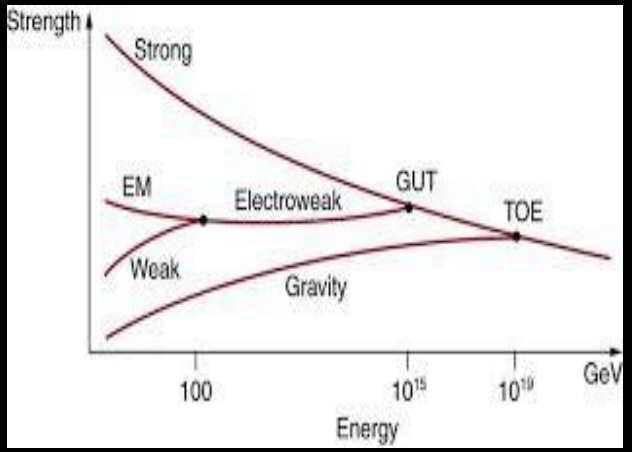


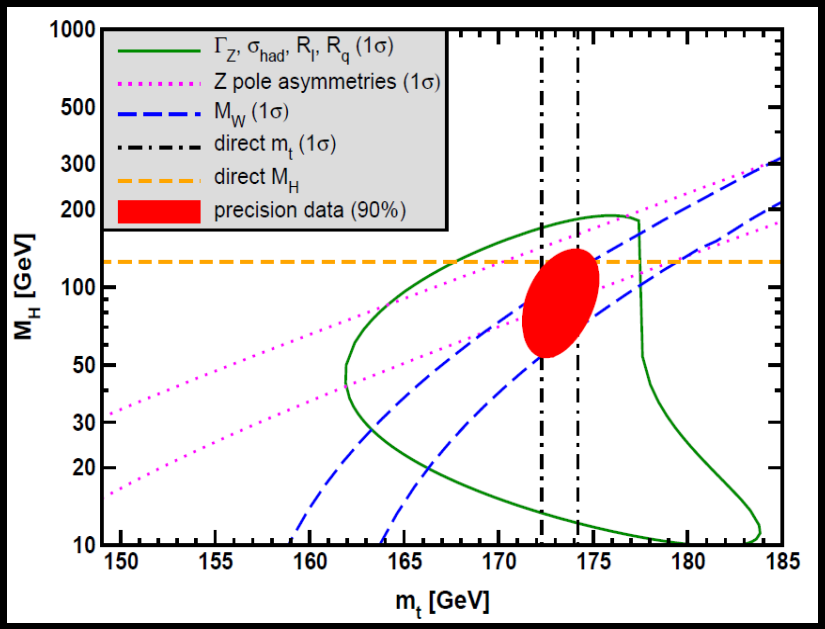
coupling unification



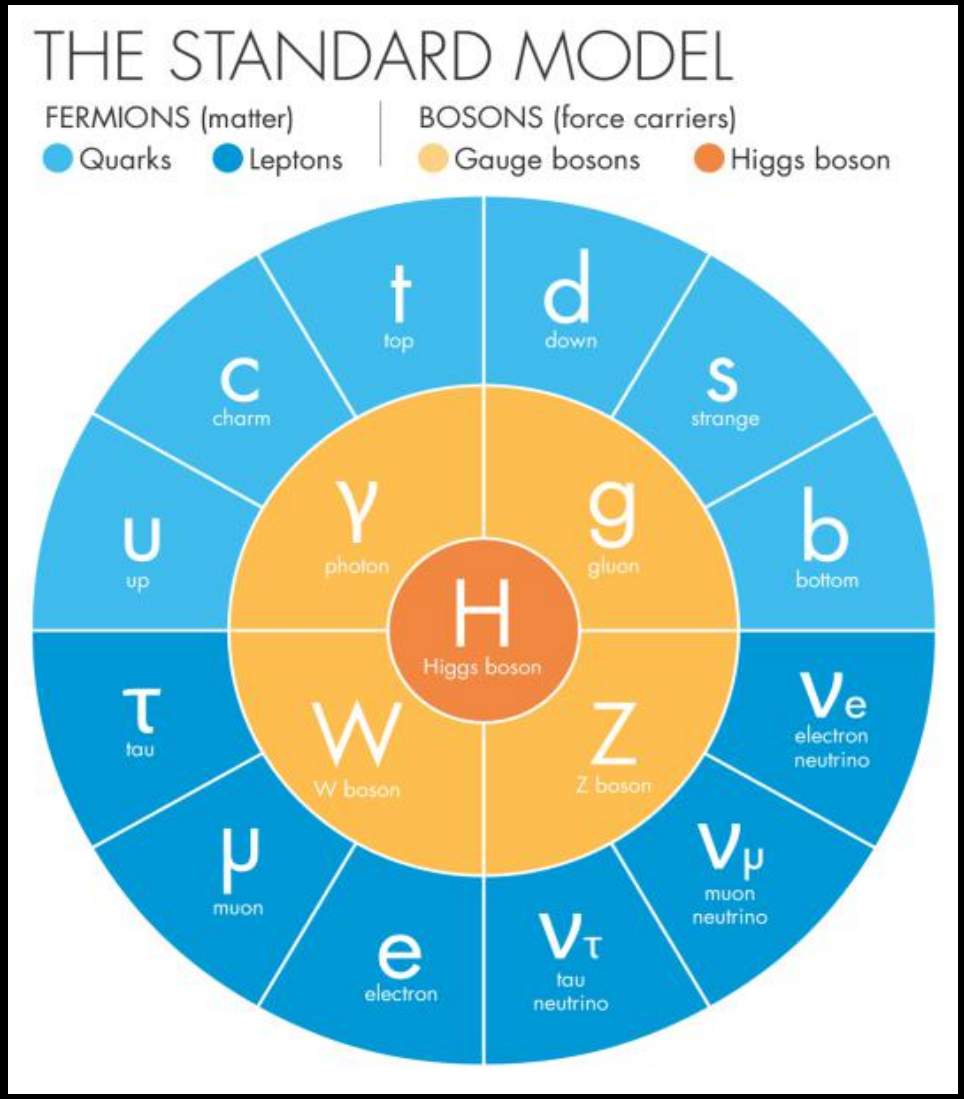
Gravity …

Neutrino mass

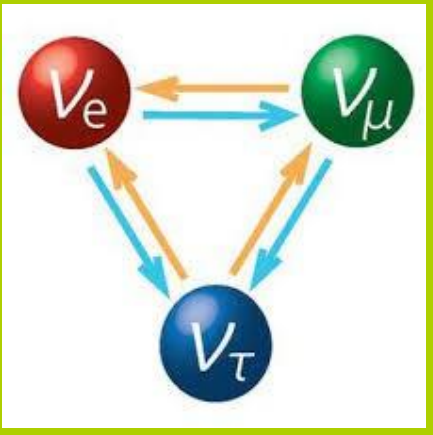
Why 3 families …



Higgs not the last brick ! ...



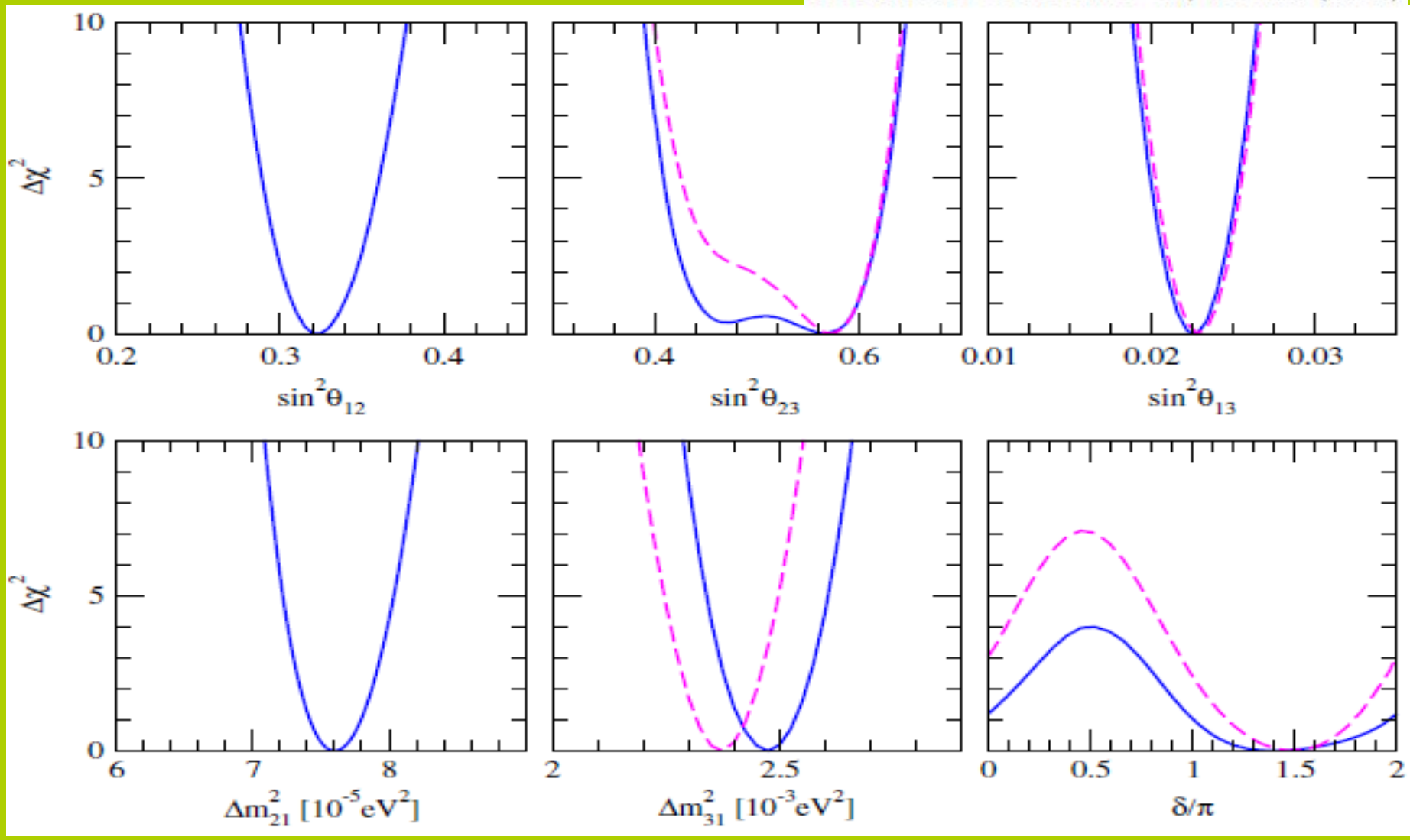
SM can not explain neutrinos

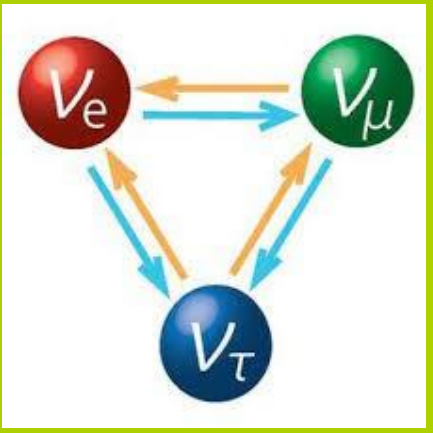


Oscillation parameters

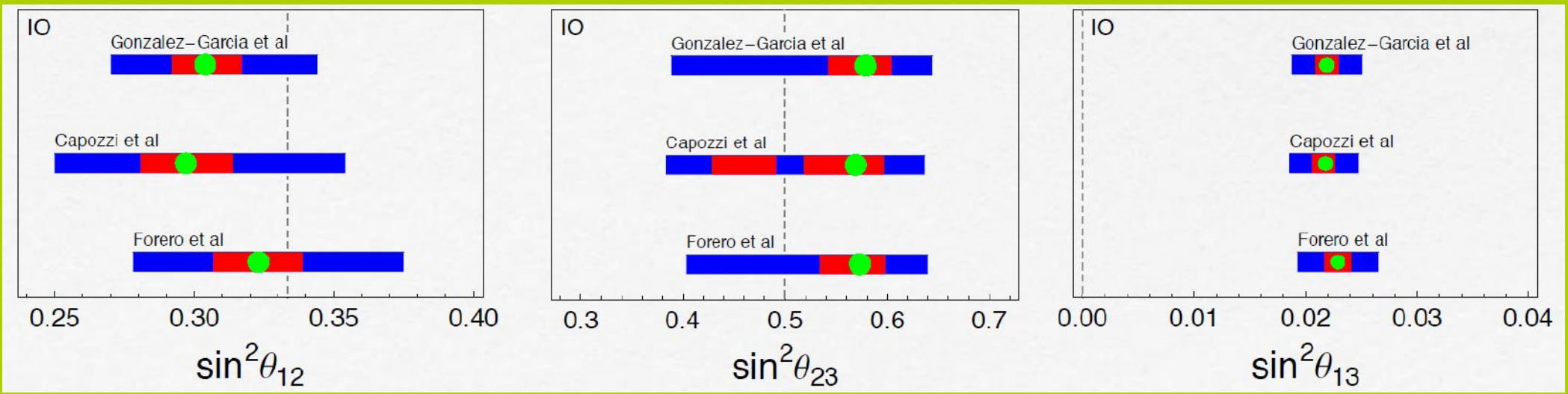
Precision era starts

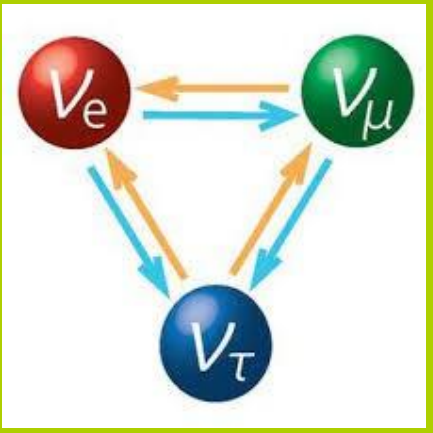
PHYSICAL REVIEW D 90, 093006 (2014)



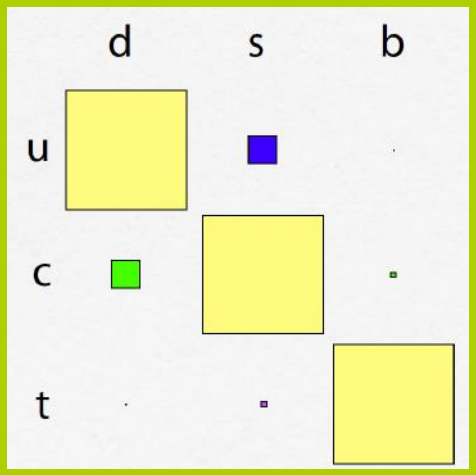


Neutrino oscillation parameters

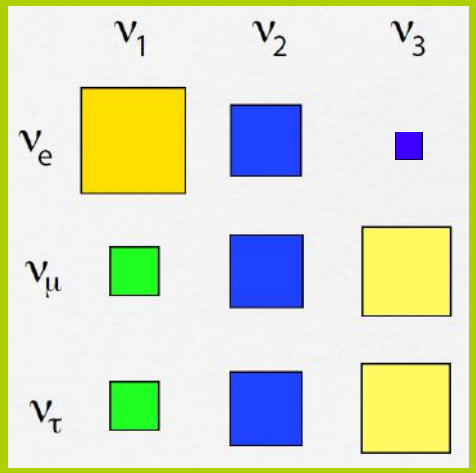


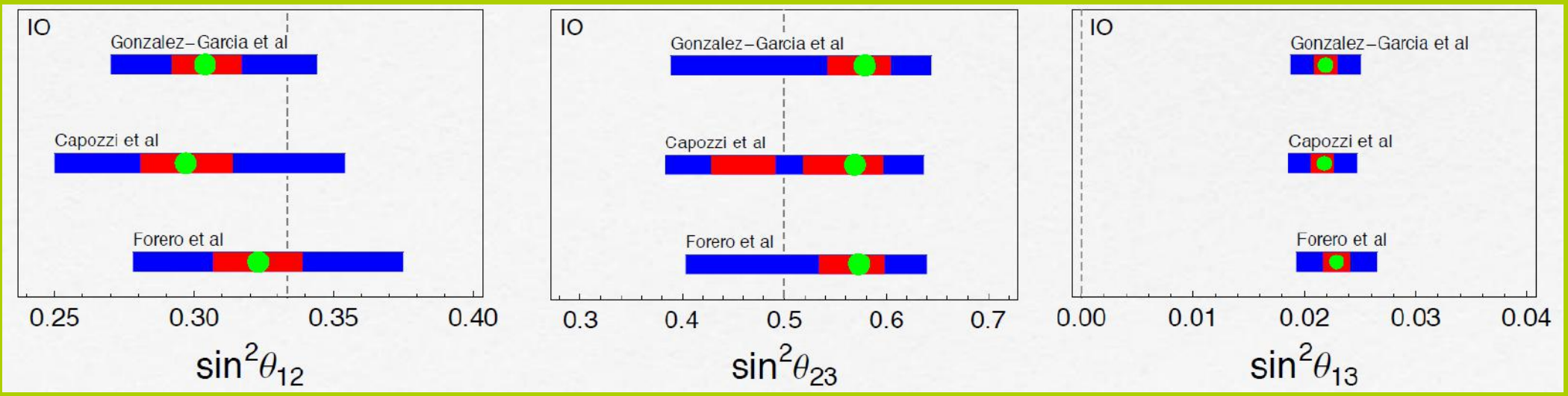


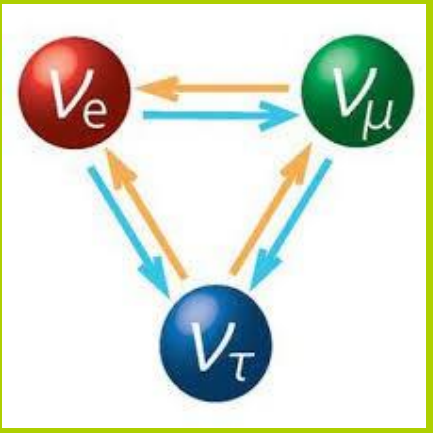
Neutrino oscillation parameters



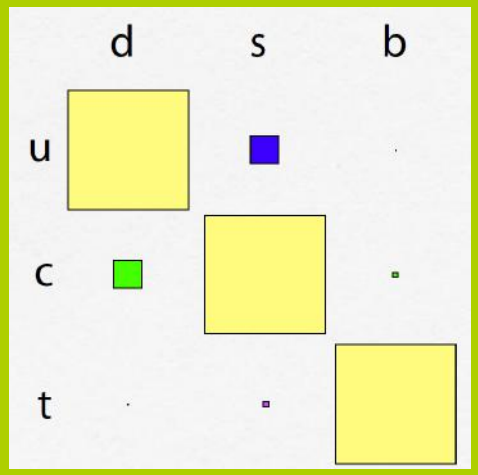
vs



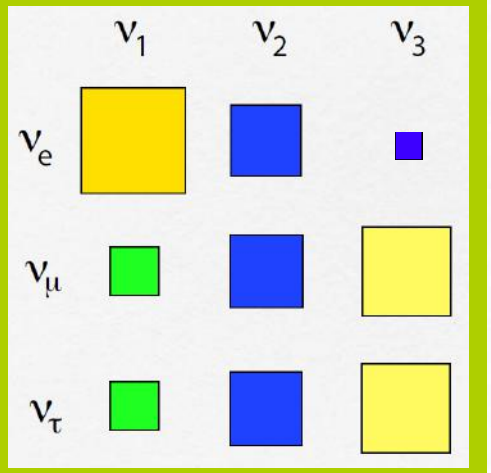


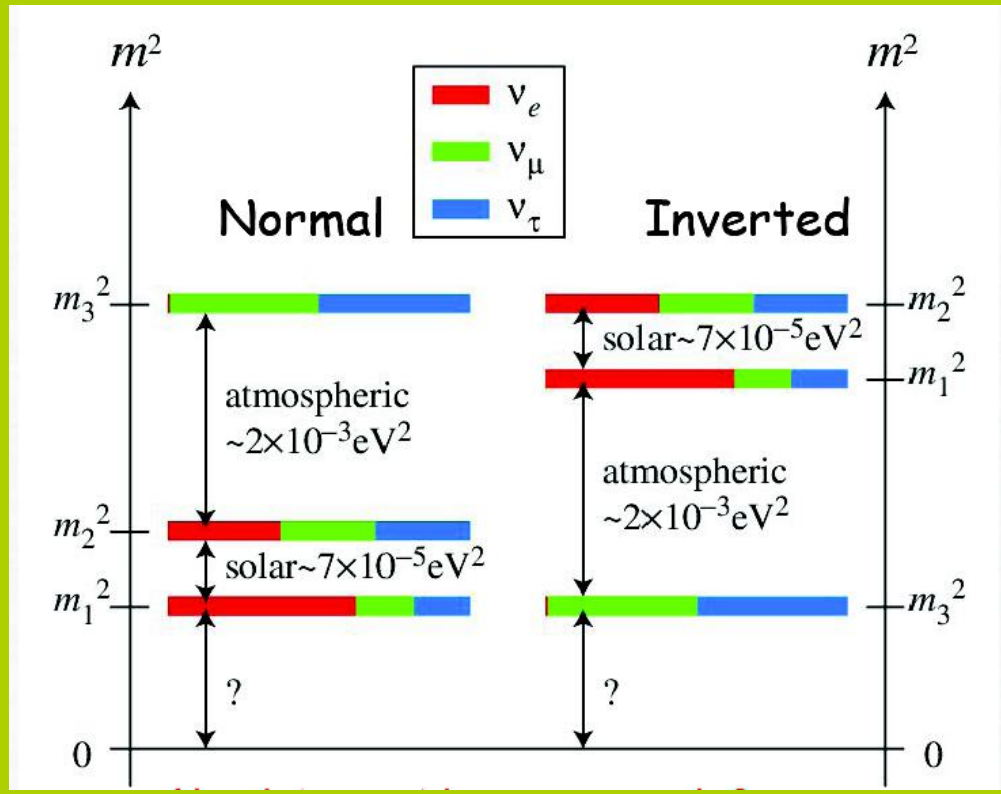


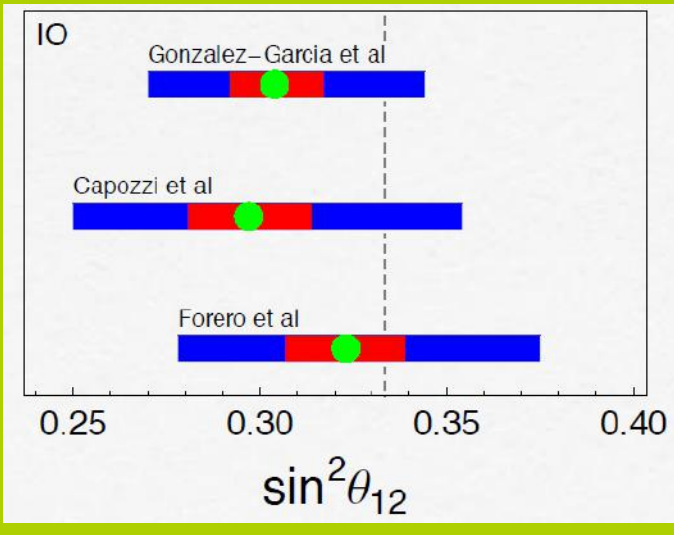
Neutrino oscillation parameters

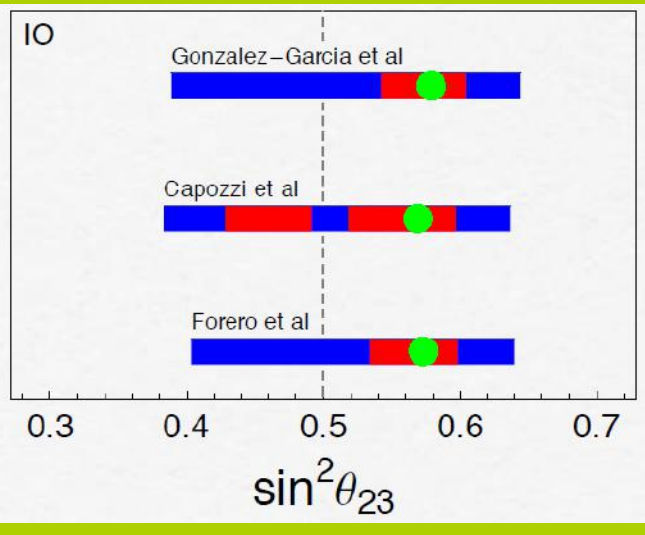


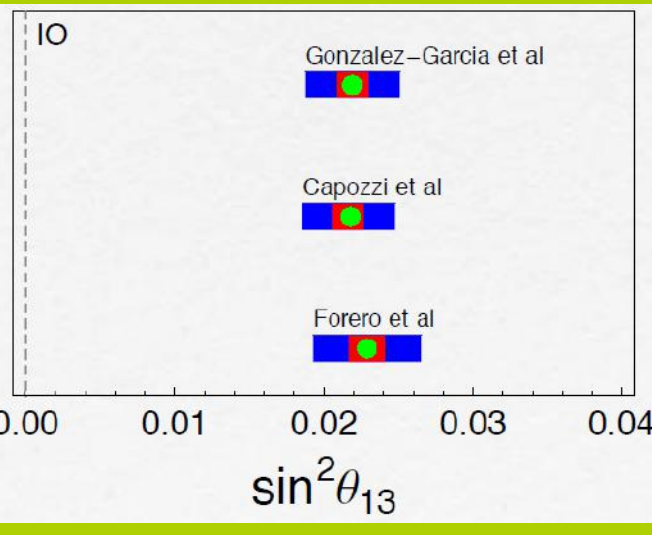
vs



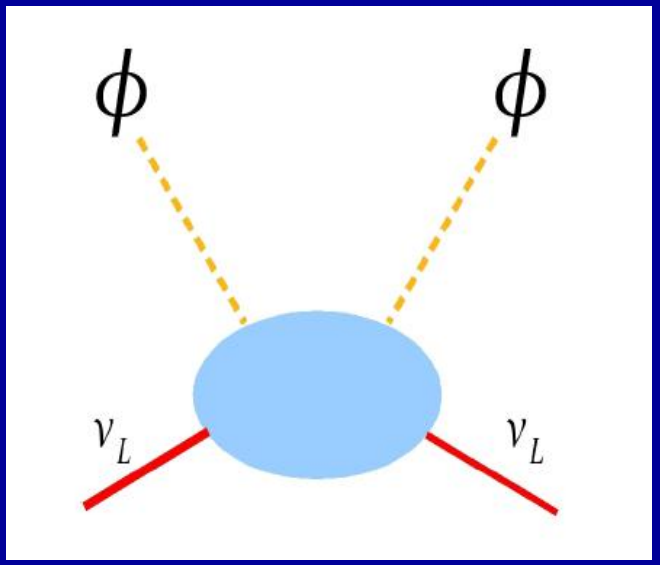








The origin of neutrino mass

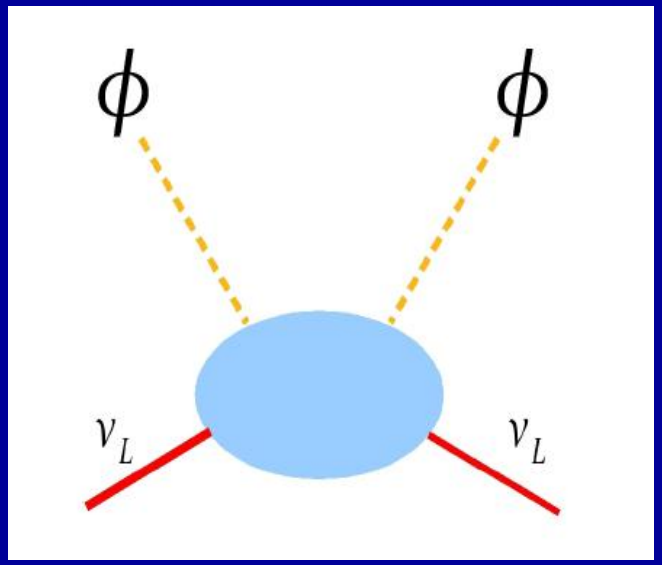


MECHANISM

SCALE

FLAVOR STRUCTURE

The origin of neutrino mass

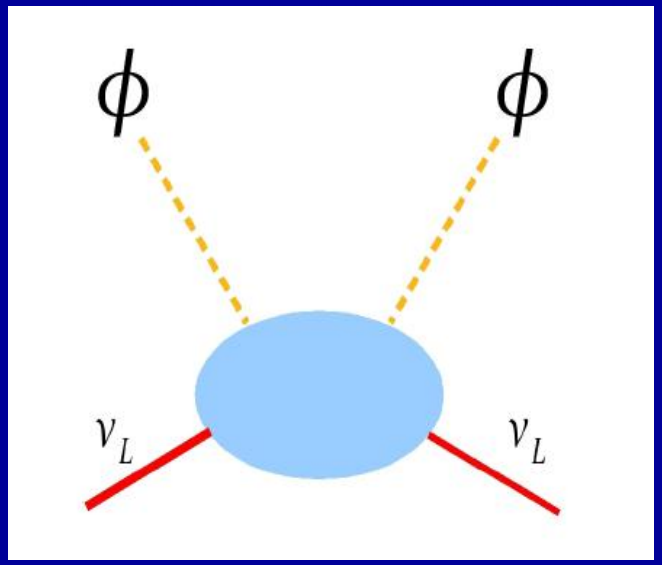


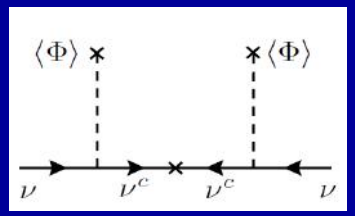
Seesaw

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

- MECHANISM
- SCALE
- FLAVOR STRUCTURE

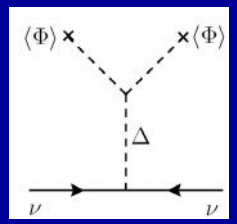
The origin of neutrino mass





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

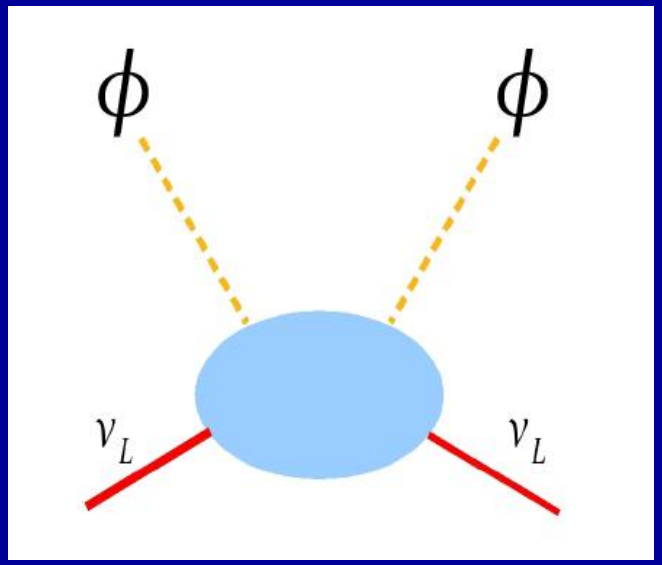
$$v_3 v_1 \sim v_2{}^2$$

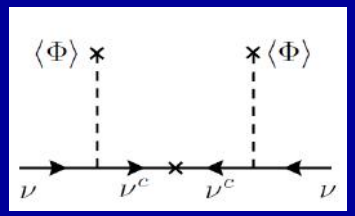
MECHANISM

SCALE

FLAVOR STRUCTURE

The origin of neutrino mass





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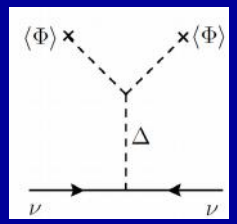


TYPE II

Schechter-Valle 80/82

Seesaw

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

MECHANISM

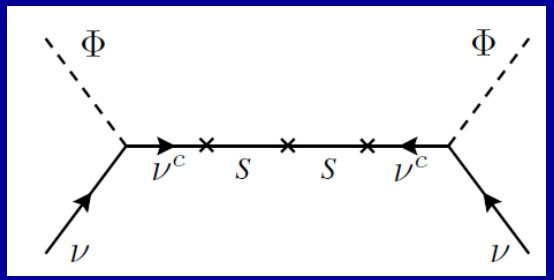
SCALE

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



Non unitary lepton mixing & CP

$$\begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

$$\alpha_{11}^2 \geq 0.989\,, \quad \alpha_{22}^2 \geq 0.999\,, \quad |\alpha_{21}|^2 \leq 6.6 \times 10^{-4}$$

Schechter & JV PRD22 (1980) 2227 & PDG

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

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

http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.117.061804

non-unitary propagation hints associated (relatively low–mass) type-I seesaw messenger responsible for inducing neutrino mass

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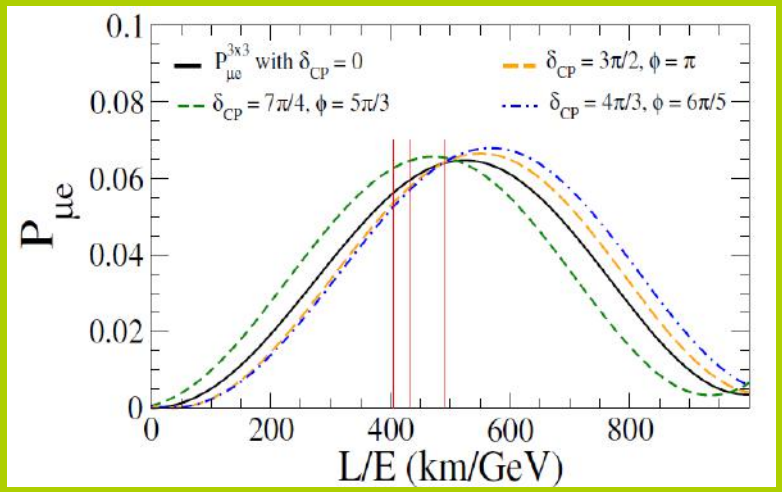
$$P_{\mu e} = \alpha_{11}^2 \alpha_{22}^2 P_{\mu e}^{3\times 3} + \alpha_{11}^2 \alpha_{22} |\alpha_{21}| P_{\mu e}^{I} + \alpha_{11}^2 |\alpha_{21}|^2$$

$$P_{\mu e}^{I} = -2 \sin 2\theta_{13} \sin\theta_{23} \sin\Delta_{31} \sin\left(\Delta_{31} + \delta_{CP} + \phi\right) - \cos\theta_{13} \cos\theta_{23} \sin 2\theta_{12} \sin 2\Delta_{21} \sin\phi,$$



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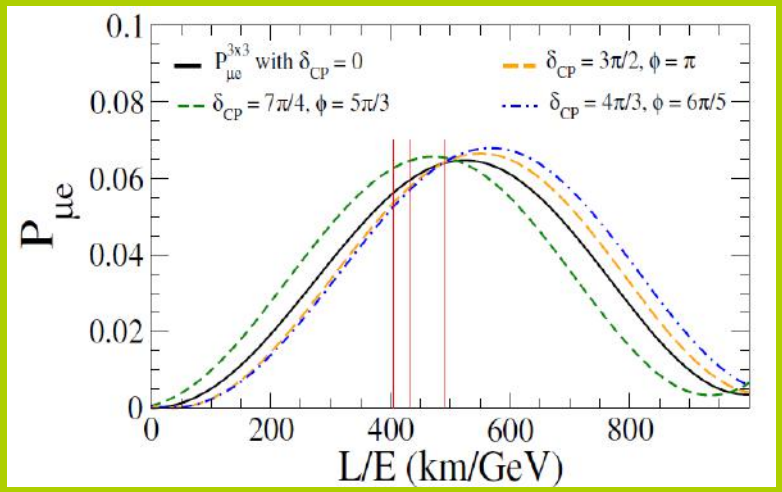
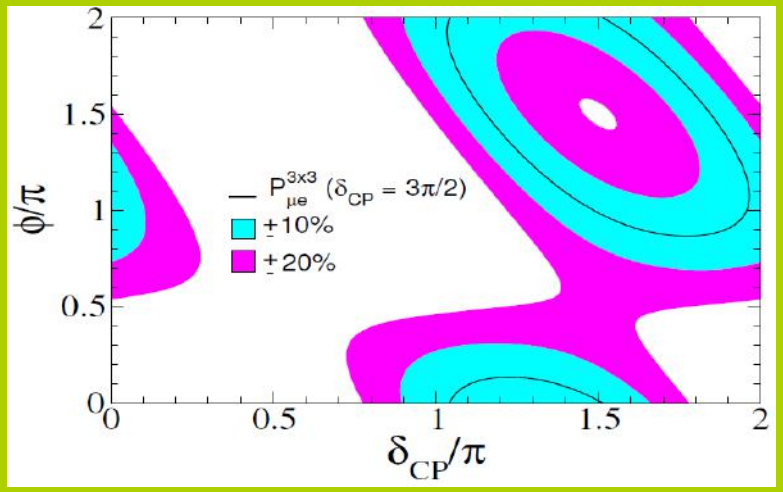
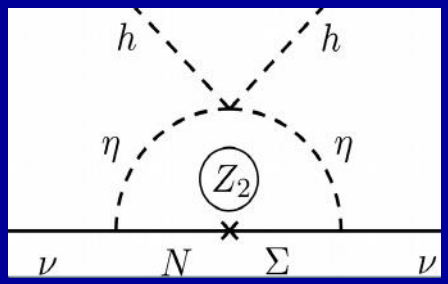


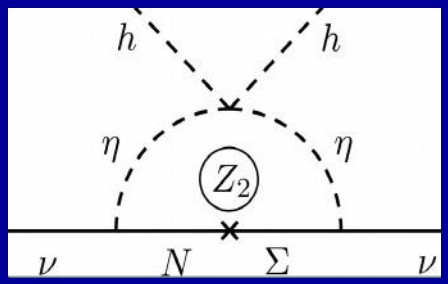




Radiative neutrino mass

many low-scale neutrino mass schemes ...

arXiv:1404.3751



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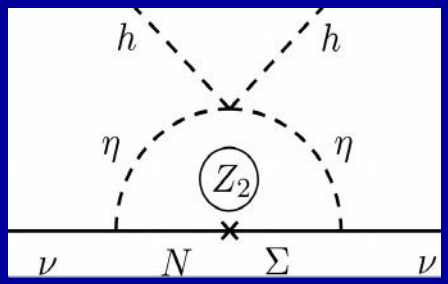
331 electroweak theory # generations = # colours

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



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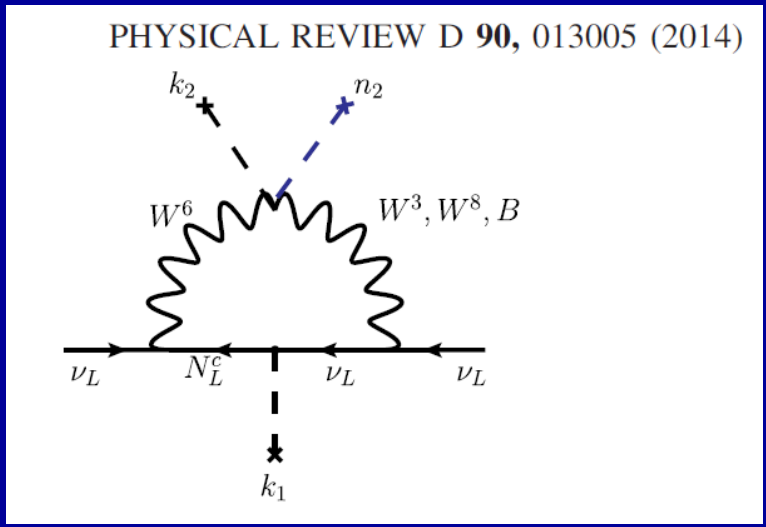
many low-scale neutrino mass schemes ...

arXiv:1404.3751

331 electroweak theory # generations = # colours

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

Gauge vs Higgs



BOUCENNA, MORISI, AND VALLE

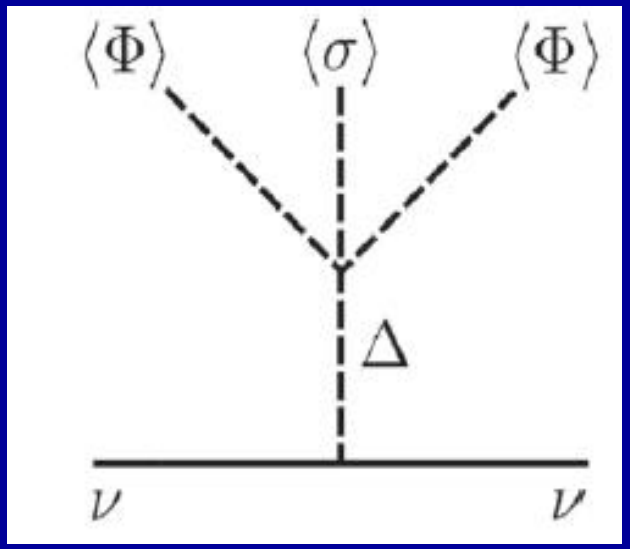
TABLE I. Matter content of the model, where $\hat{u}_R \equiv (u_R, c_R, t_R, t'_R)$ and $\hat{d}_R \equiv (d_R, s_R, b_R, d'_R, s'_R)$ (see text).

	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	$+\frac{2}{3}$	$-\frac{4}{3}$	$+\frac{2}{3}$

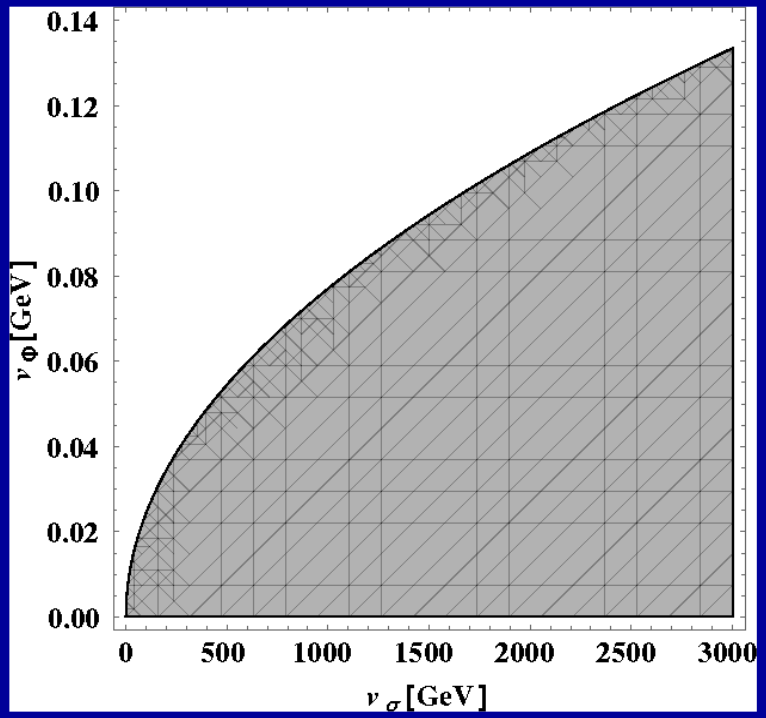
$$Q = T_3 + \frac{1}{\sqrt{3}} T_8 + X, \qquad (2)$$

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

Majoron & Diracon type-II seesaw

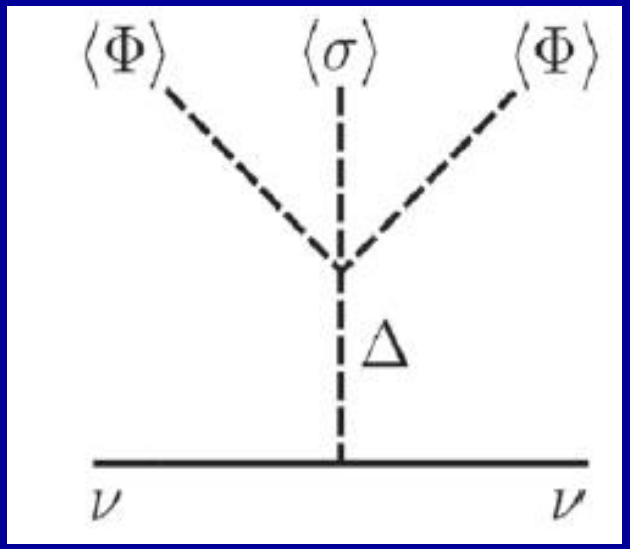


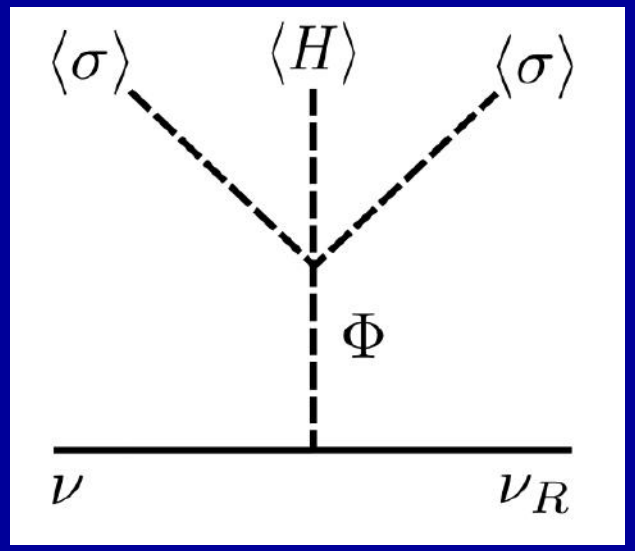
- Astrophysical limit



Majoron & Diracon type-II seesaw

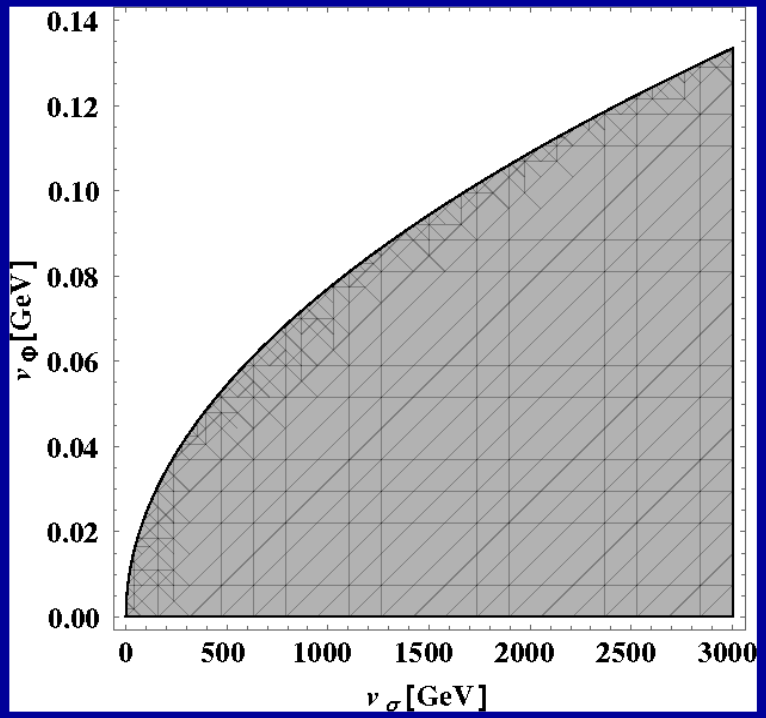
- Lepton # from accidental global U(1)
- Naturally small induced vev





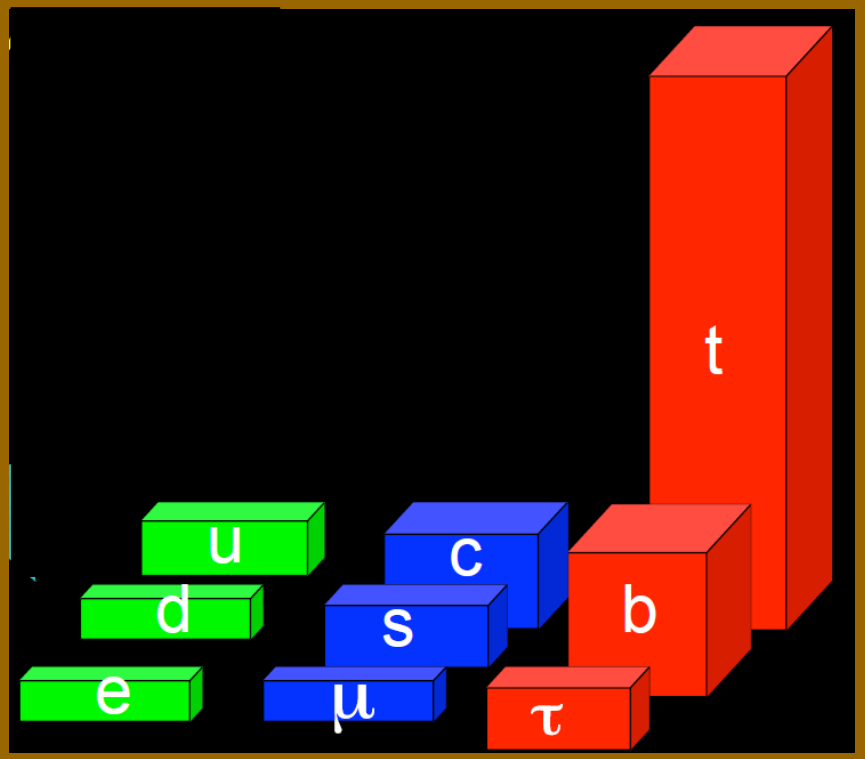
ArXiv:1605.08362 PLB

- Astrophysical limit



Flavor puzzle

masses

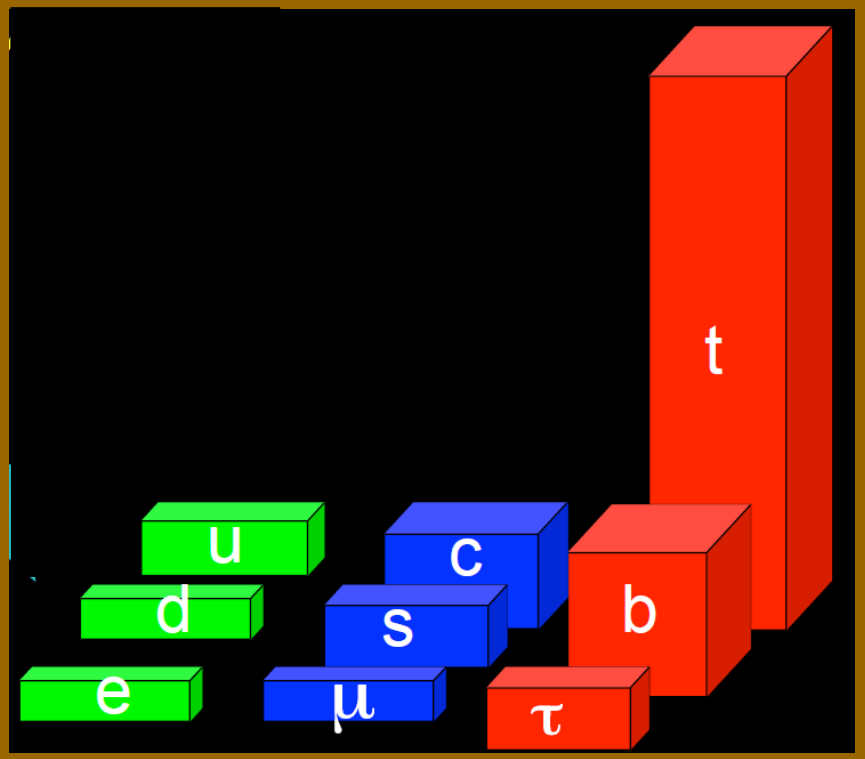


Neutrinos : Lepton number?

mixings

Flavor puzzle

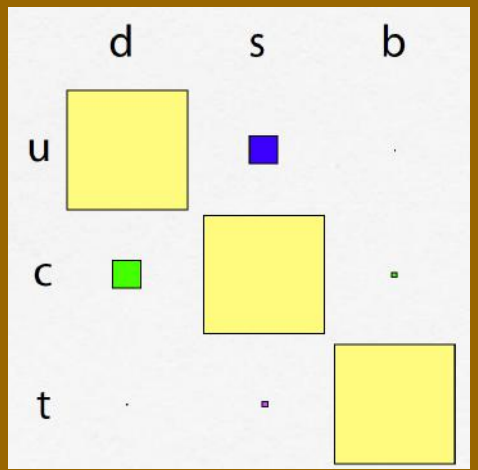
masses



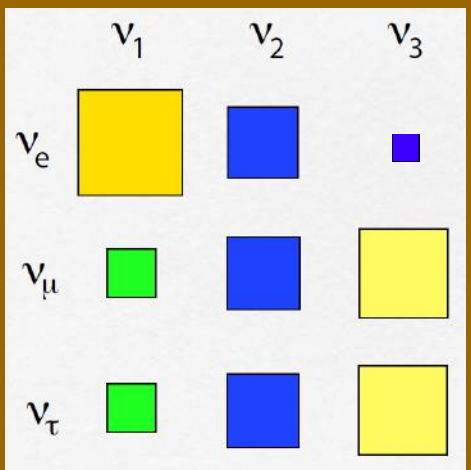
b-tau unification

Neutrinos : Lepton number?

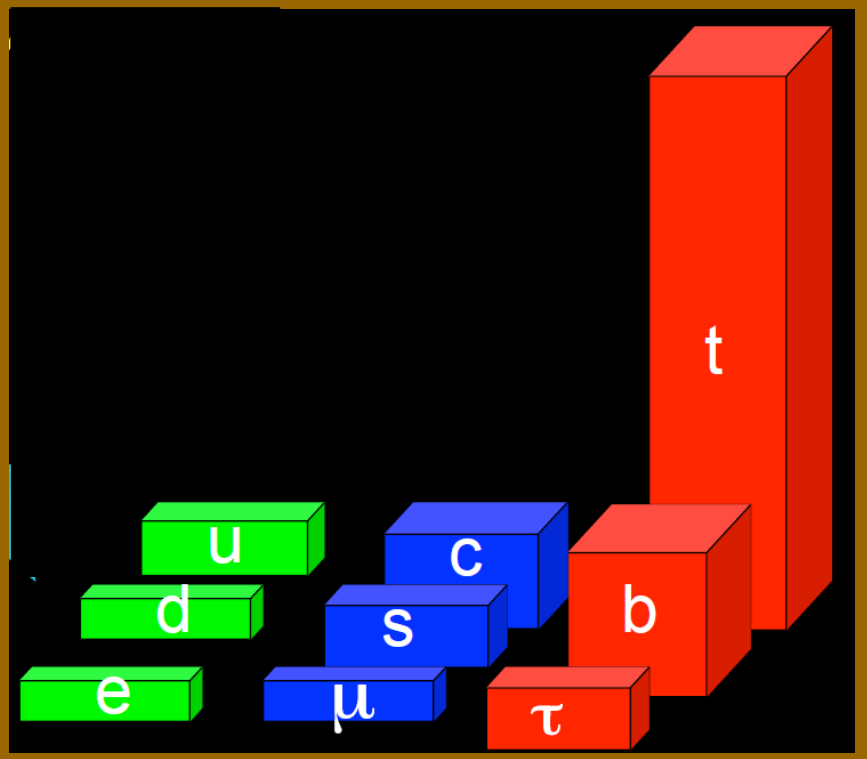
mixings



vs



Flavor puzzle



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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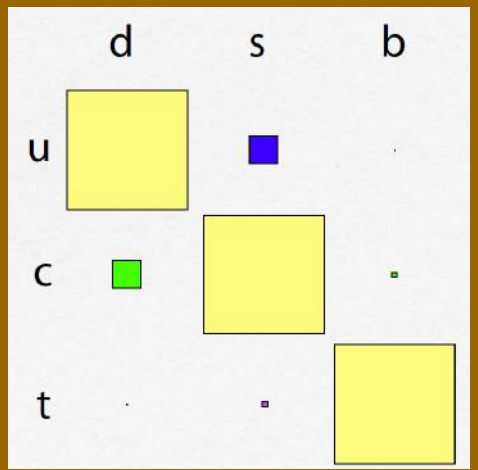
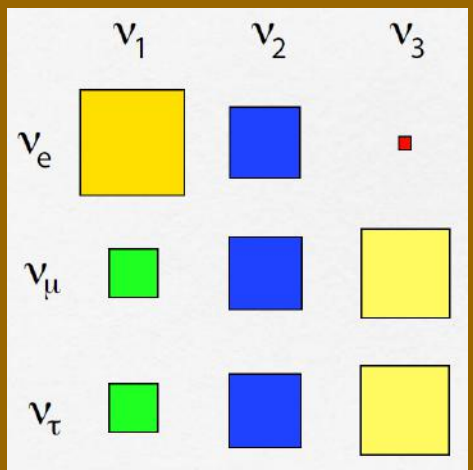
mixings



vs



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

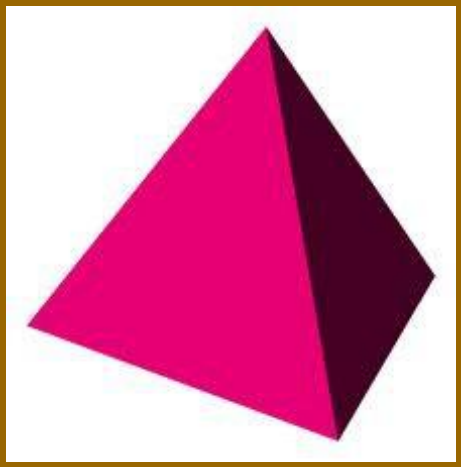
$$e_R \qquad \mu_R \qquad \tau_R$$

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

$$u_R \qquad c_R \qquad t_R$$

$$d_R \qquad s_R \qquad b_R$$

Flavor Symmetry



A4

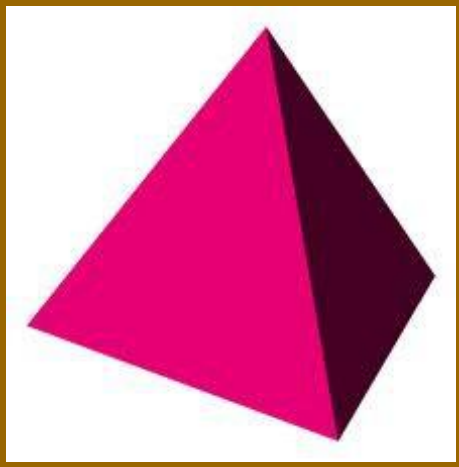
Babu-**Ma**-Valle PLB552 (2003) 207
Hirsch et al PRD69 (2004) 093006

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

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

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

Flavor Symmetry



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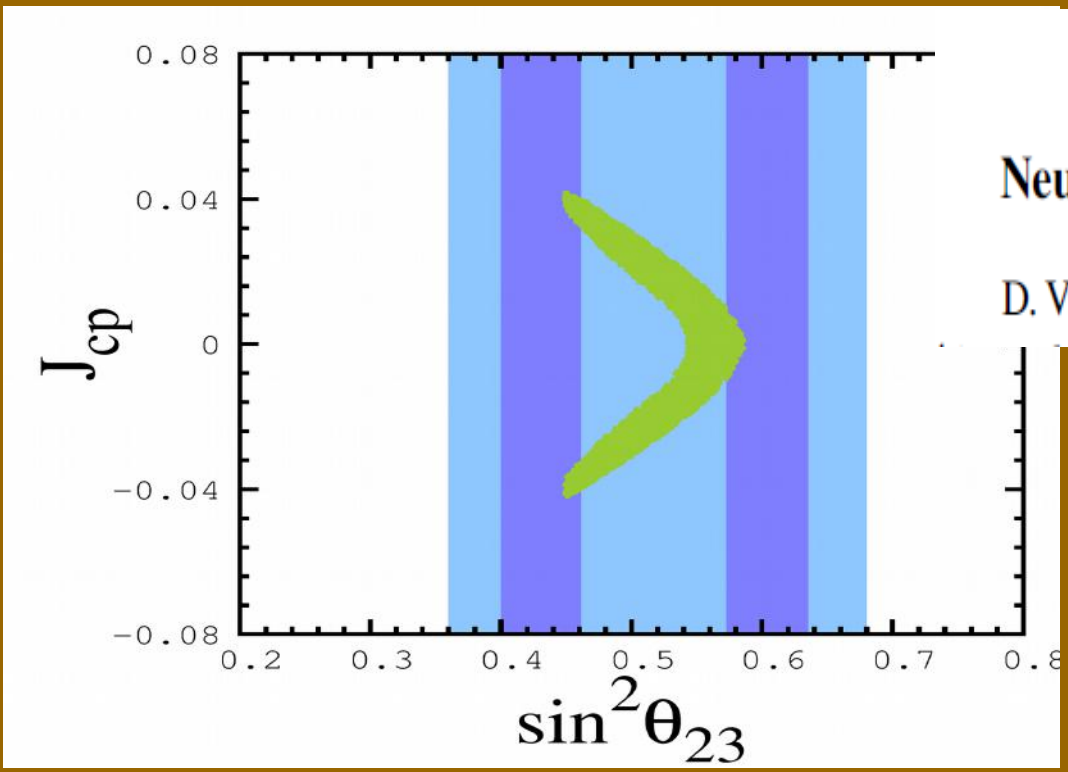


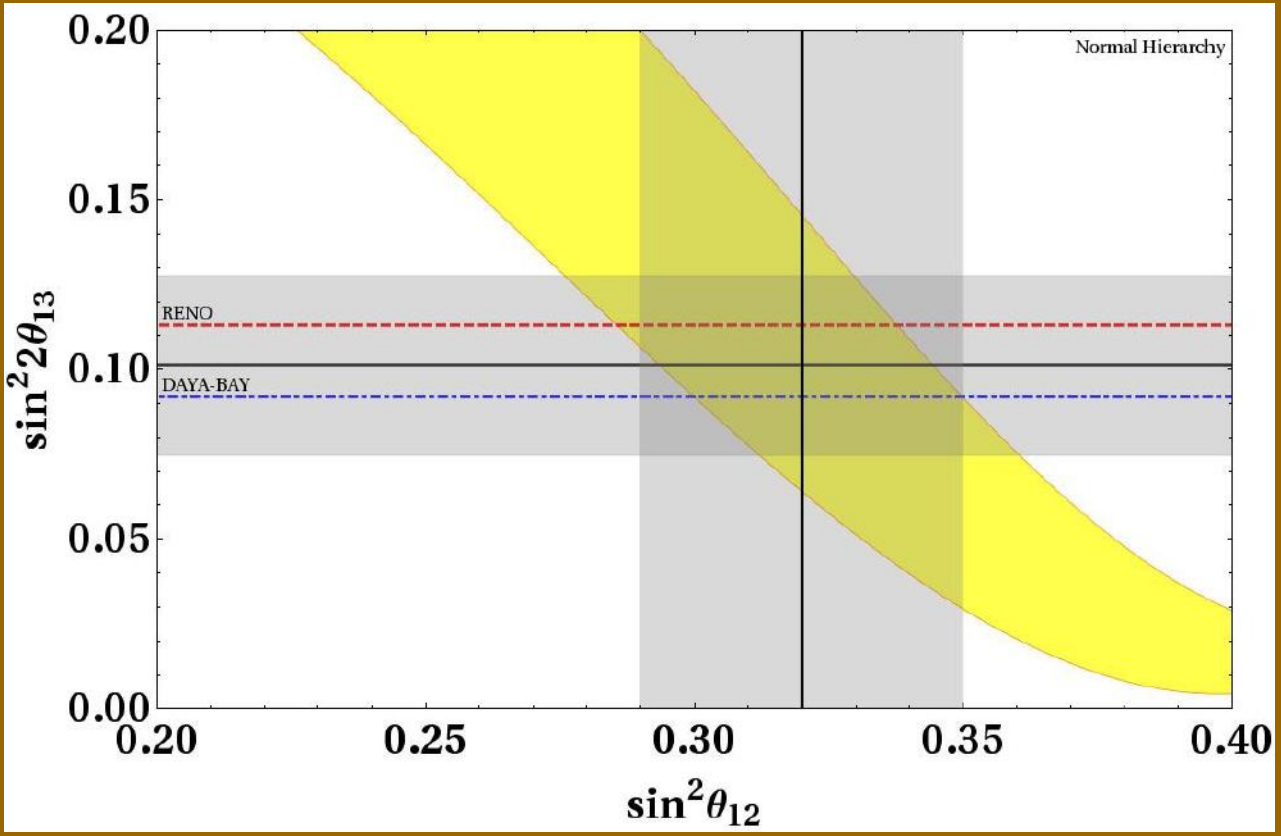
PHYSICAL REVIEW D 88, 016003 (2013)

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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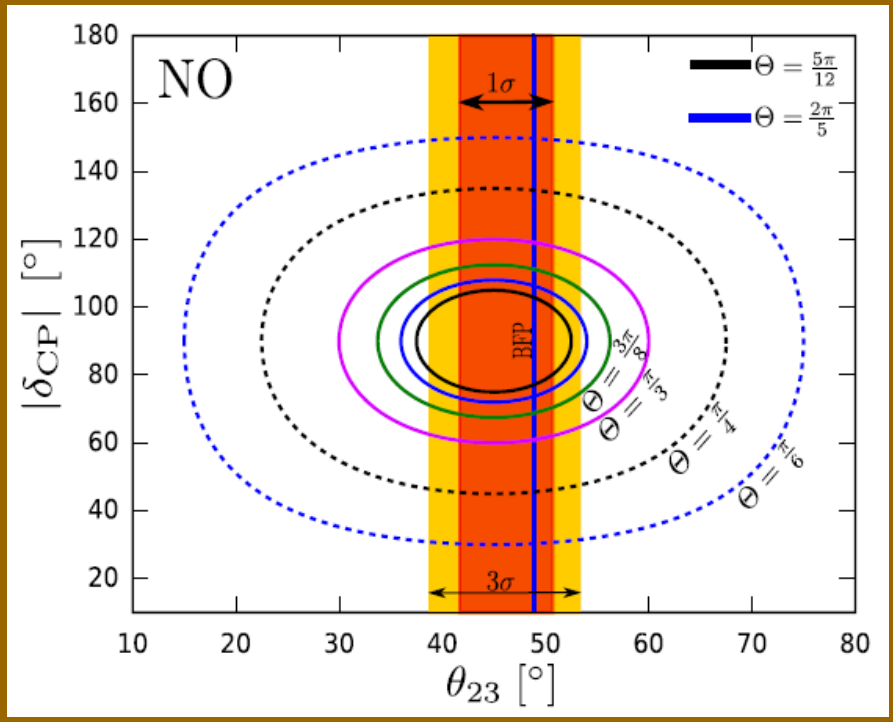

P. Chen et al. / Physics Letters B 753 (2016) 644–652

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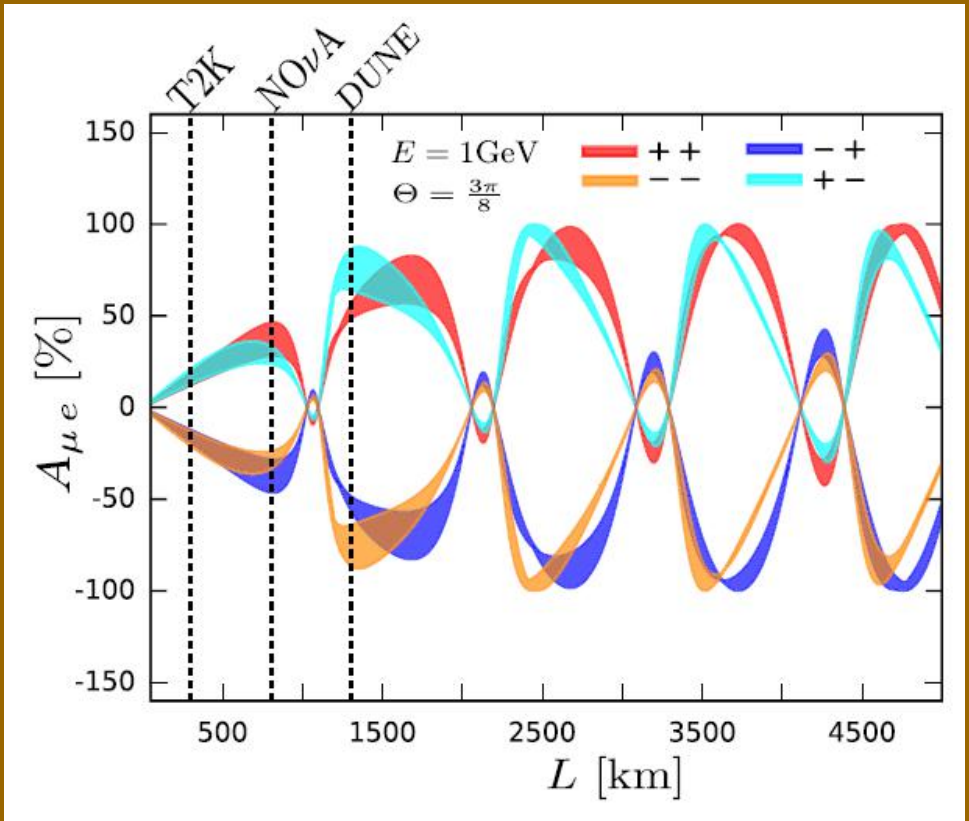
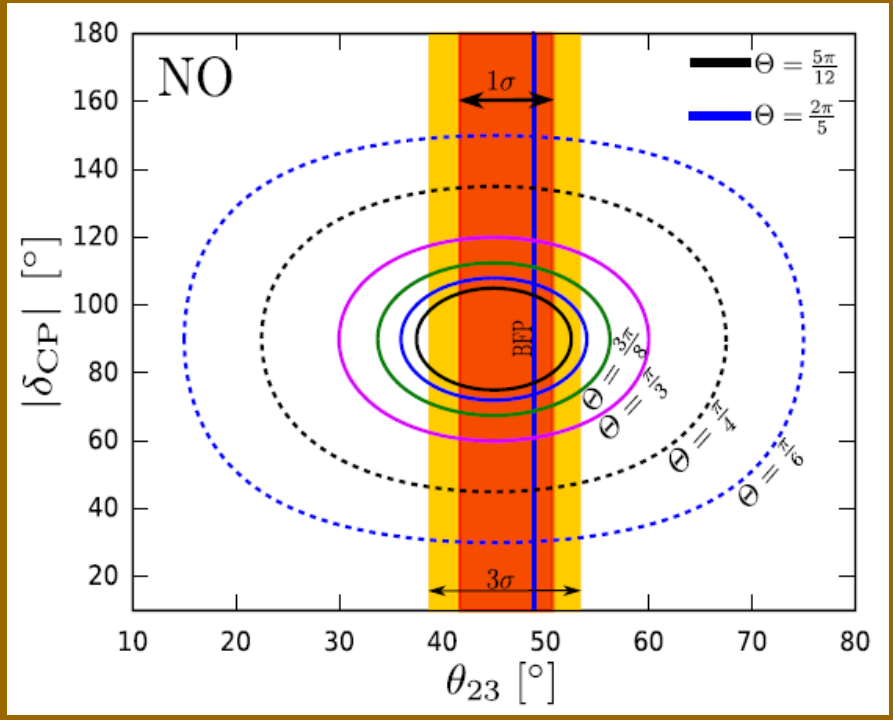
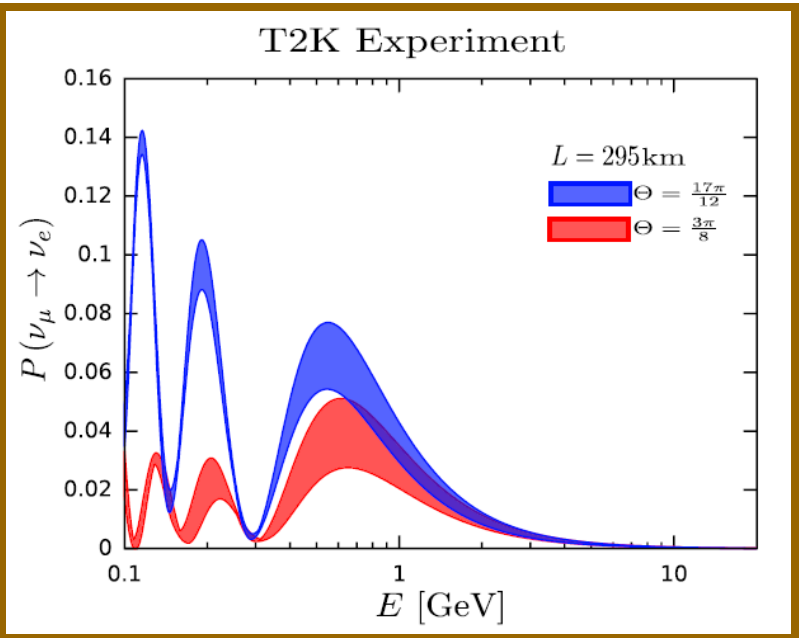
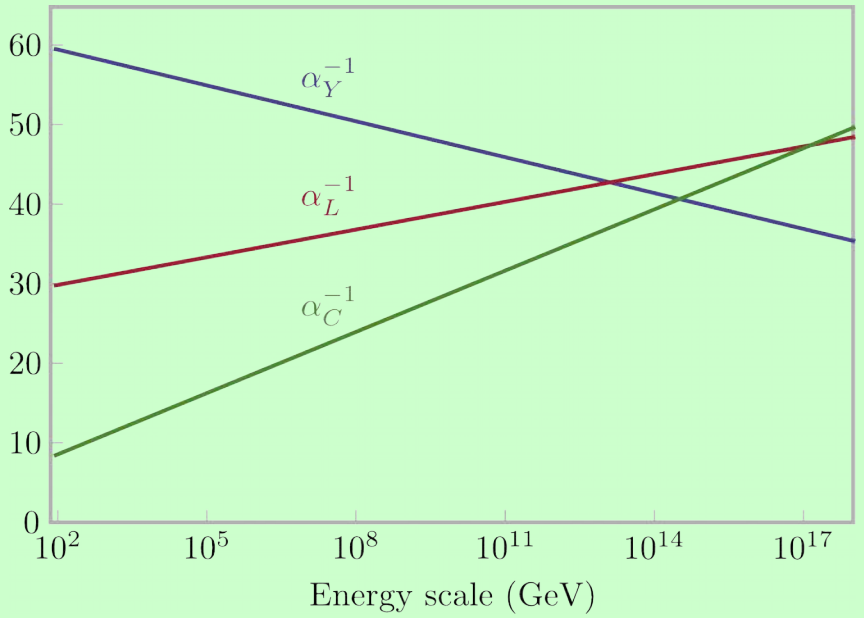






Gauge coupling unification

a near miss ...



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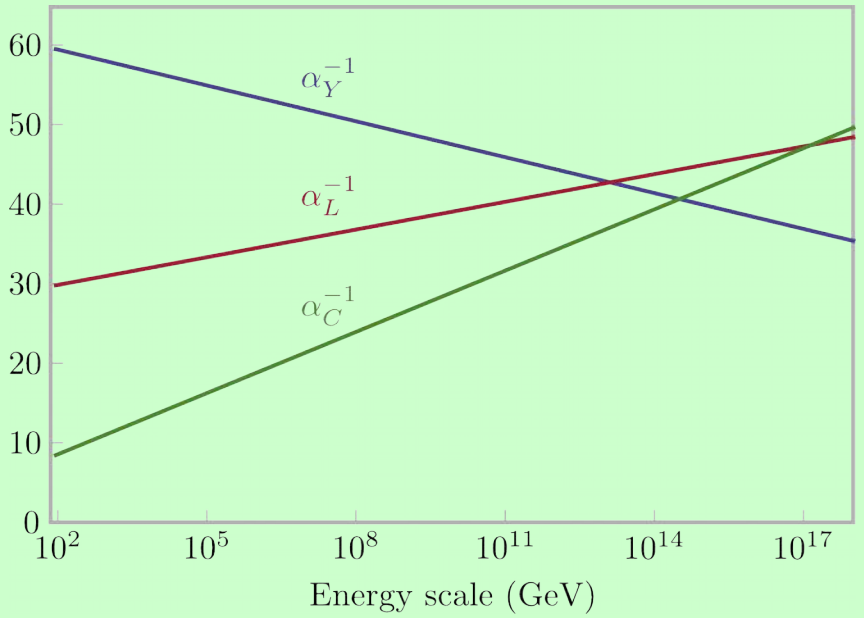

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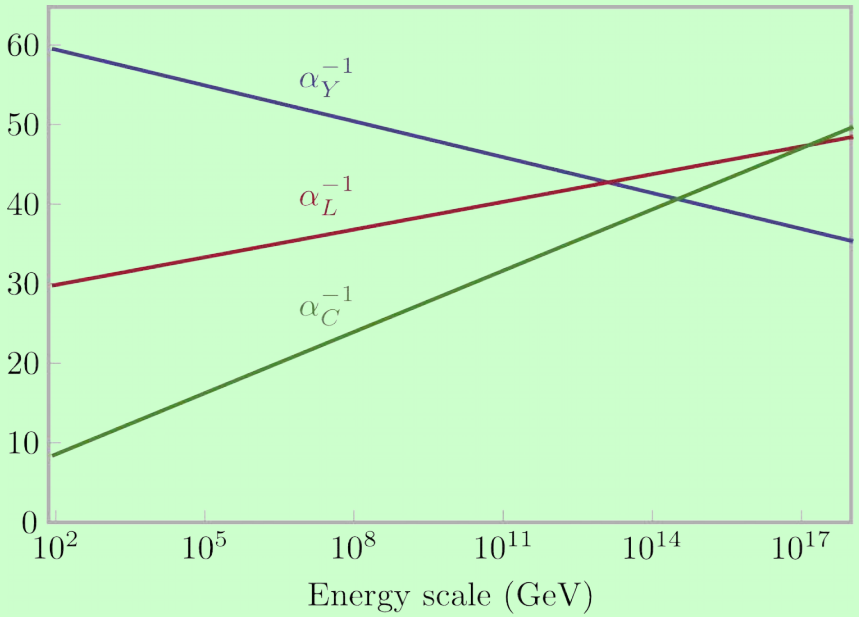
But … p decay, sparticles …

Gauge coupling unification



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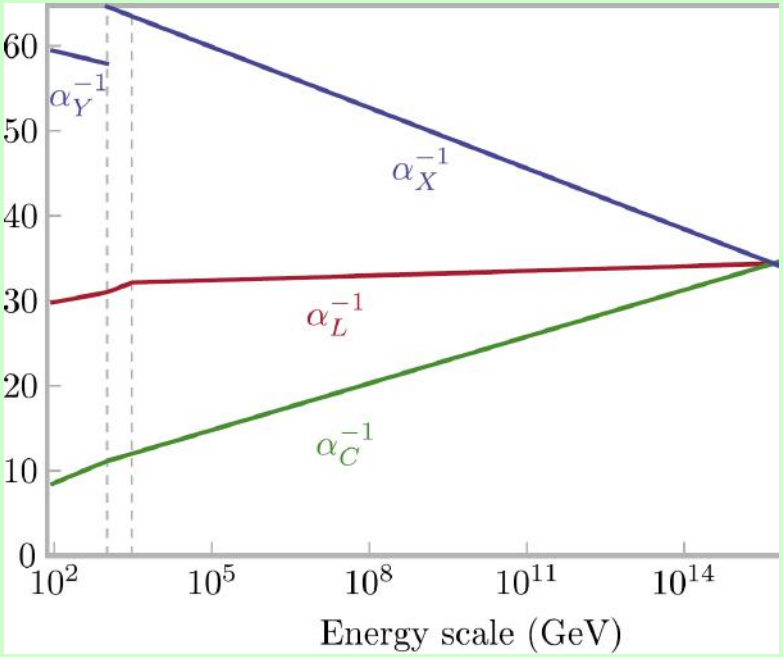


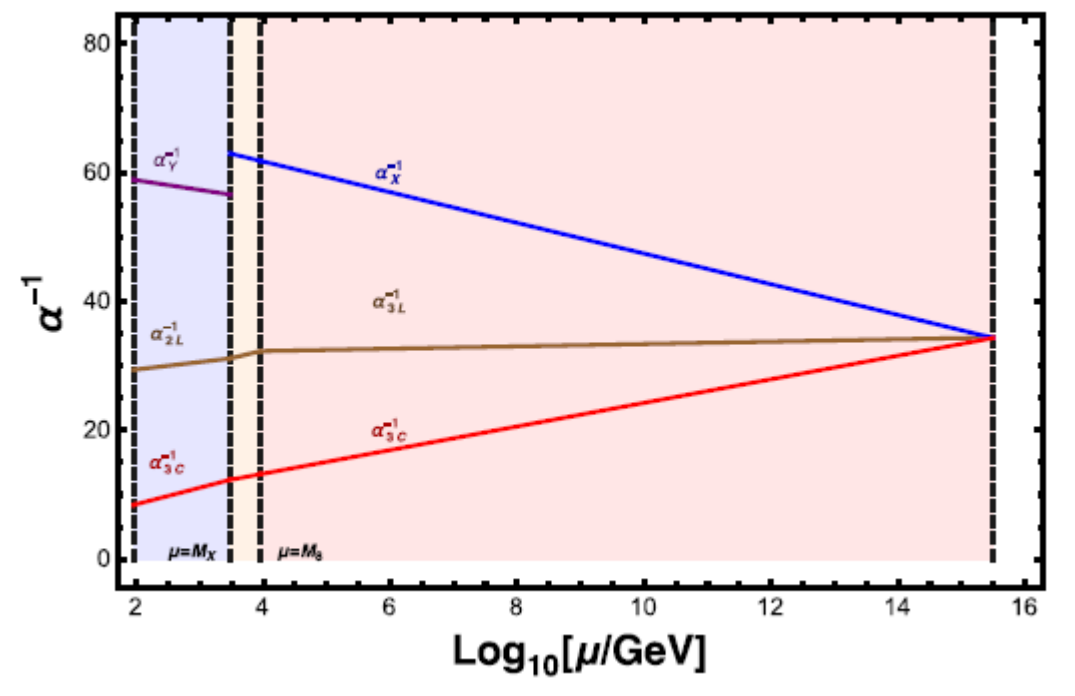
neutrino

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

Phys. Rev. D 91, 031702 (2015)

Boucenna, Fonseca, Gonzalez-Canales, JV

unification without conventional GUT embedding



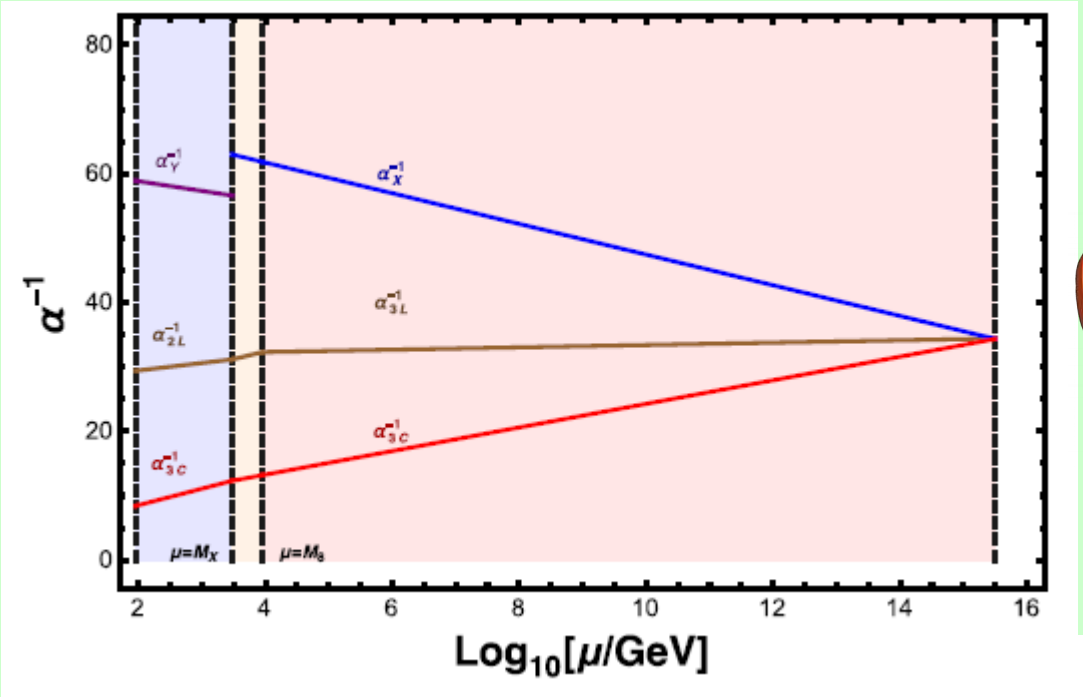
Deppisch et al 1608.05334

SVS case: F-theory GUTs

King, Leontaris et al

unification without conventional GUT embedding

Deppisch et al 1608.05334

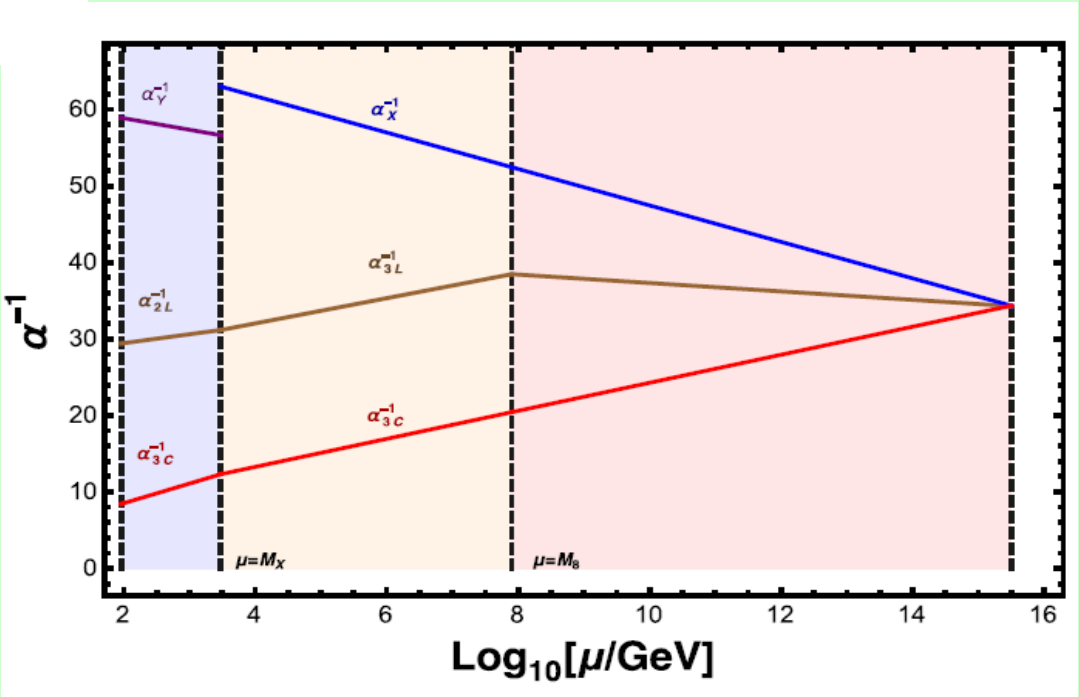


SU(6) unification of 331 EW model

Sequential case

SVS case: F-theory GUTs

King, Leontaris et al



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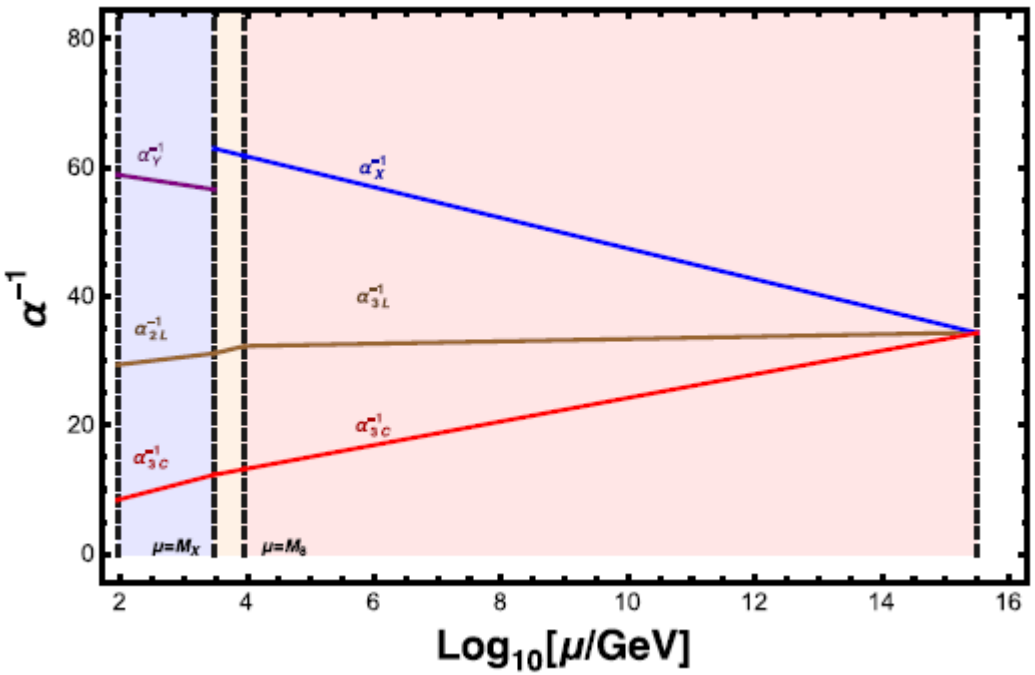

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$$\Gamma^{-1}(p \to e^+\pi^0) \sim 10^{36}\ \mathrm{yrs} \left(\frac{\alpha_{\mathrm{GUT}}^{-1}}{35}\right)^2 \left(\frac{M_U}{10^{16}\ \mathrm{GeV}}\right)^4$$