neutrinos and what comes next

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BSM-2021: from 29-03 to 02-04 2021

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Faculty of Engineering and Natural Sciences at Sabancı University

ASTROPARTICLES
Astroparticles and High Energy Physics Group

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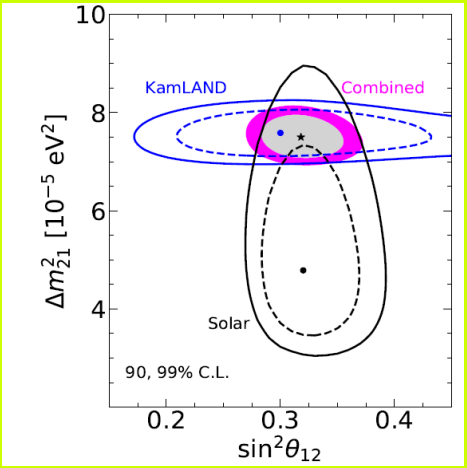
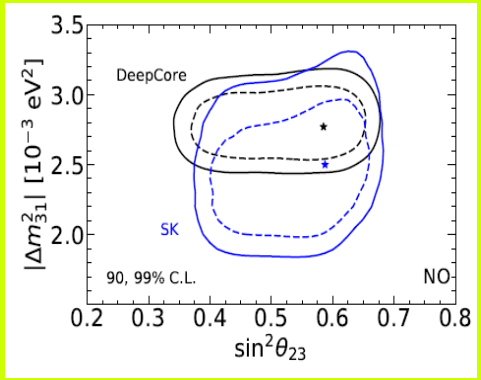
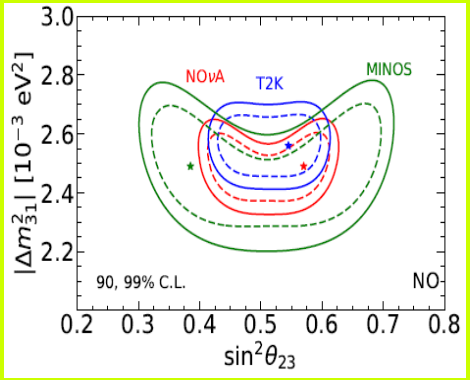
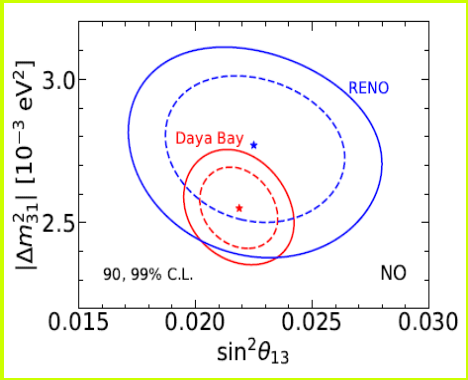
GENERALITAT VALENCIANA Conselleria d'Educació, Investigació, Cultura i Esport

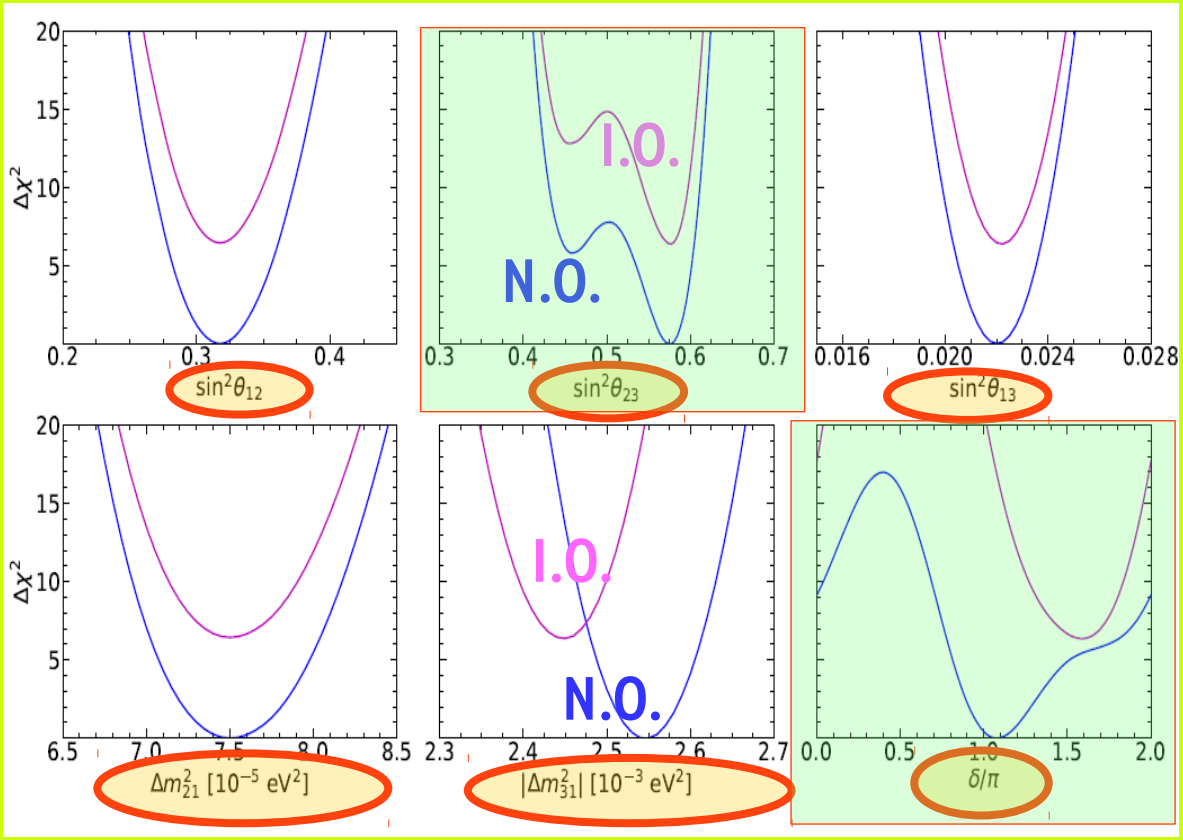
neutrino oscillations status











consistent global picture in which the solar + atm discovery measurements are confirmed and improved

Improvement needed !!
CP, ATM octant & ordering

P.F. de Salas et al **JHEP 02 (2021) 071**

https://www.astroparticles.es/

https://zenodo.org/record/4593330#.YFoBVWNKjIo

revamping TBM

Harrison, Scott & Perkins 2002

$$\begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

θ_{13}

CP

predicting solar

$$\sin^2\theta_{12} = \frac{\cos^2\theta}{\cos^2\theta + 2},$$

$$\sin^2\theta_{13} = \frac{\sin^2\theta}{3},$$

$$\sin^2\theta_{23} = \frac{1}{2} + \frac{\sqrt{6}\sin 2\theta \sin\sigma}{2\cos^2\theta + 4}$$

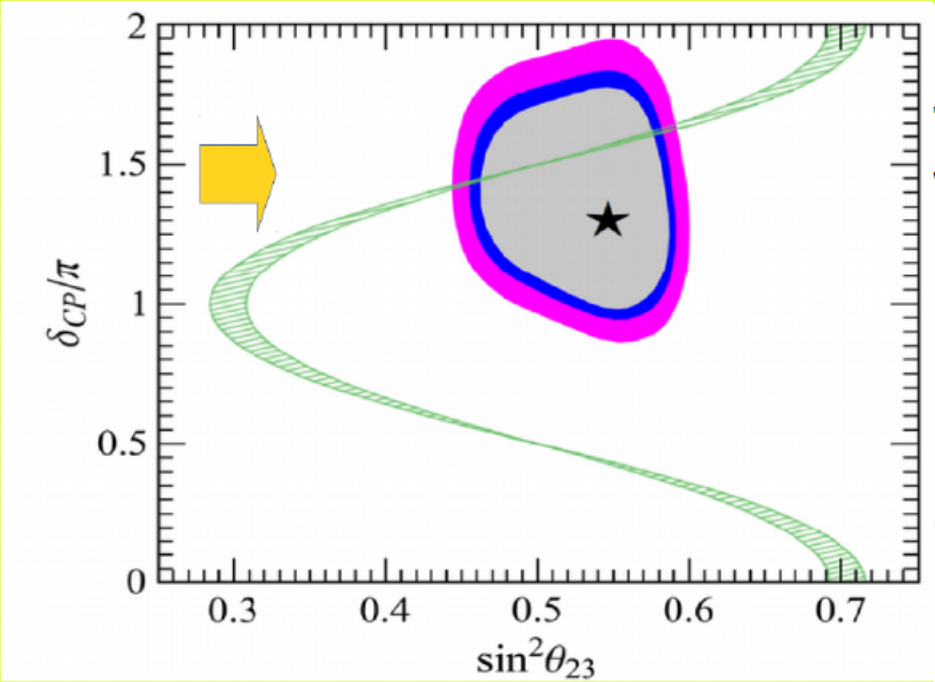
$$\tan\delta_{CP} = \frac{(\cos^2\theta + 2)\cot\sigma}{5\cos^2\theta - 2},$$

PHYSICAL REVIEW D **98,** 055019 (2018)

systematic

Chen et al
Phys.Lett. B753 (2016) 644
Phys.Rev. D94 (2016) 033002
JHEP 1807 (2018) 077
Phys.Lett. B792 (2019) 461
Phys.Rev. D99 (2019) 075005

predicting CP



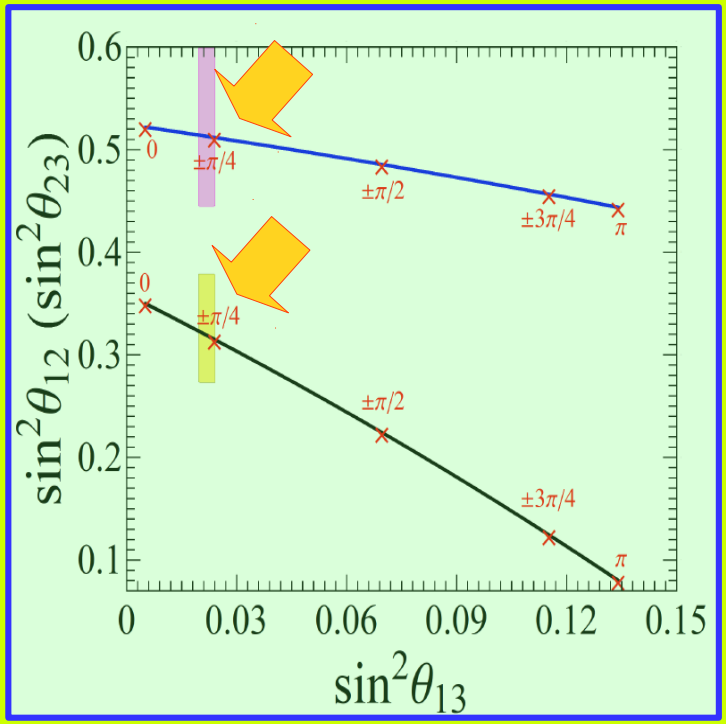
Bi-Large lepton mixing pattern

$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & -\lambda e^{i\phi} & A\lambda^3 e^{i\phi} \\ \lambda e^{-i\phi} & 1-\frac{1}{2}\lambda^2 & -A\lambda^2 \\ 0 & A\lambda^2 & 1 \end{bmatrix} \qquad \begin{bmatrix} 1-\frac{5\lambda^2}{2} & 2\lambda & -\lambda \\ -2\lambda+3\lambda^2 & 1-\frac{13\lambda^2}{2} & 3\lambda \\ \lambda+6\lambda^2 & -3\lambda+2\lambda^2 & 1-5\lambda^2 \end{bmatrix}$$

Largest Q-mixing similar to smallest L-mixing
Cabibbo angle as universal seed for flavor mixing

Phys.Rev. D86 (2012) 051301
Phys.Rev.D87 (2013) 053013
Phys.Lett. B748 (2015) 1-4

$\sin\theta_{12}^{\rm CKM} = \lambda$ and $\sin\theta_{23}^{\rm CKM} = A\lambda^2$, where $\lambda = 0.22453 \pm 0.00044$, $A = 0.836 \pm 0.015$



From
Phys.Lett. B792 (2019) 461

predicting
solar + atm
from reactor

for "softer" version of Bi-Large see

Phys.Lett.B 796 (2019) 162

$0\nu\beta\beta$

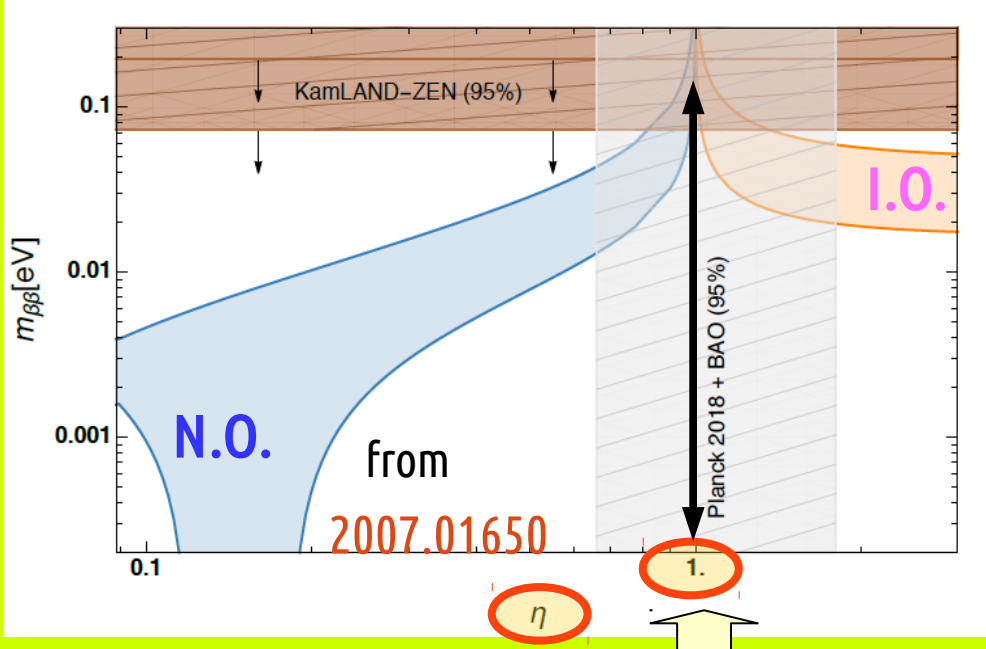
$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{2\phi_{12}} + s_{13}^2 m_3 e^{2\phi_{13}}|$$

Schechter & JV PRD22 (1980) 2227

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

- **Quasi-degenerate nearly excluded**

Lattanzi, Gerbino, Freese, Kane, Valle
JHEP 10 (2020) 213



degeneracy parameter

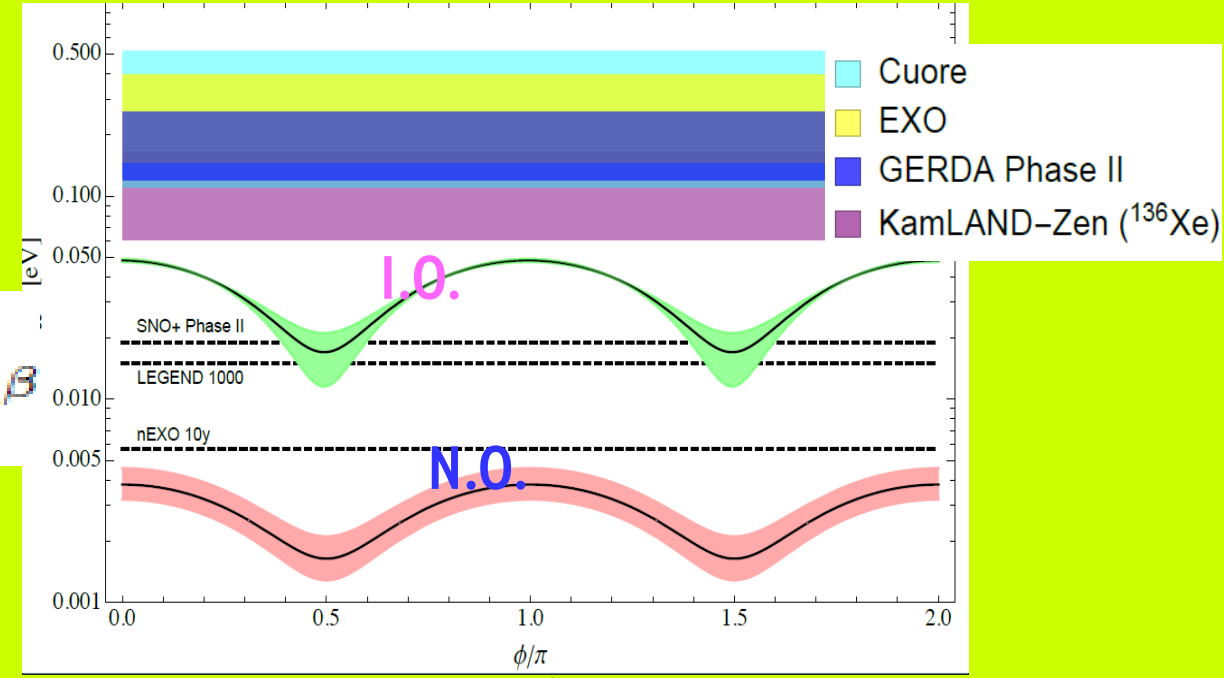
- **one-massless**

Reig et al Phys.Lett. B790 (2019)303

Barreiros, Felipe & Joaquim
JHEP 01 (2019) 223

Avila et al Eur.Phys.J.C 80 (2020) 10, 908

$m_{\beta\beta}$



majorana phase

flavor sensitivity neutrinoless doublebeta decay

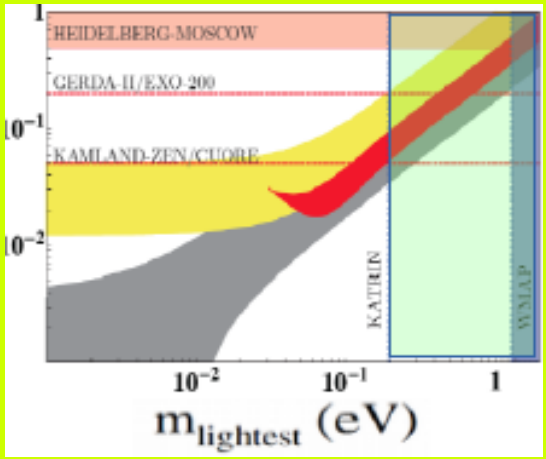
lower bounds even for normal ordering

Dorame et al
NPB861 (2012) 259-270

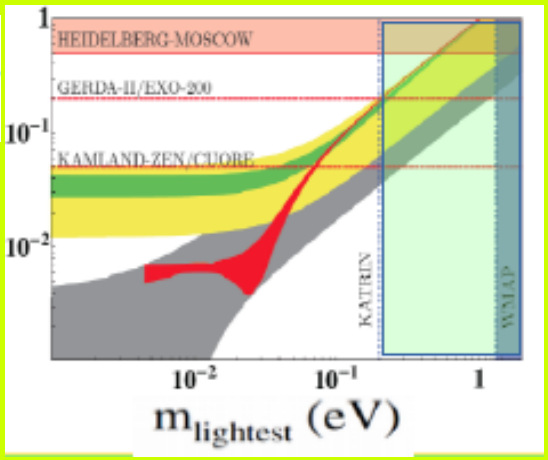
Dorame et al
PhysRevD.86.056001

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

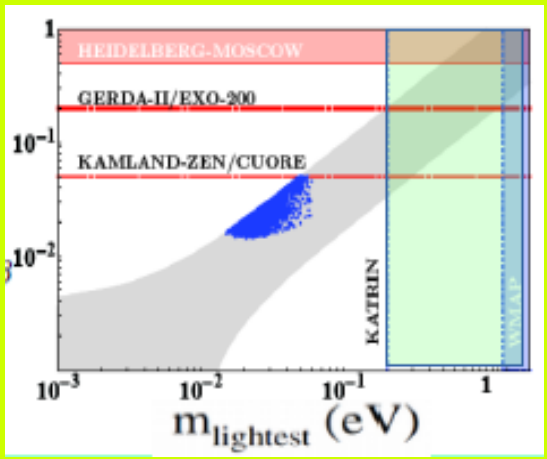
$m_{\beta\beta}$



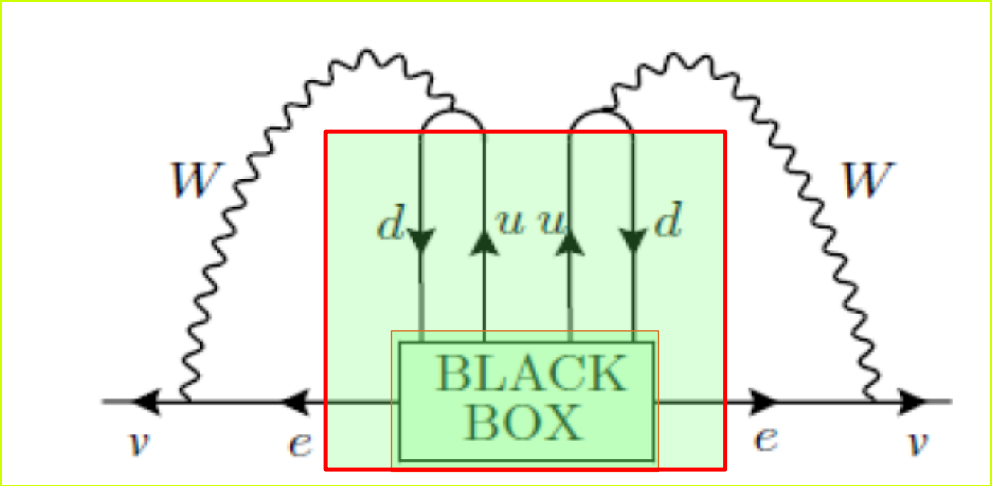
$m_{\beta\beta}$



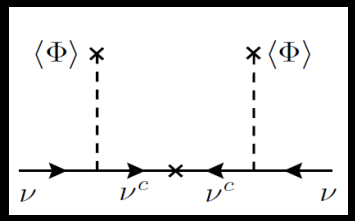
$m_{\beta\beta}$



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

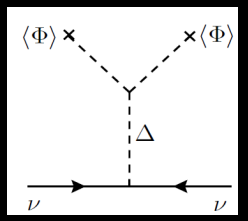


Origin of neutrino mass



TYPE I

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

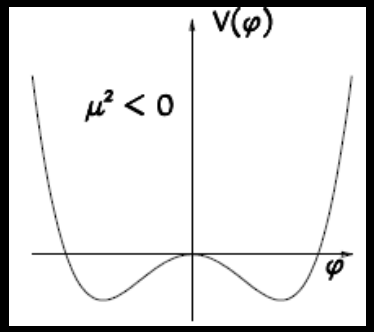


TYPE II

Schechter-Valle 80 & 82

SEESAW dynamics

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

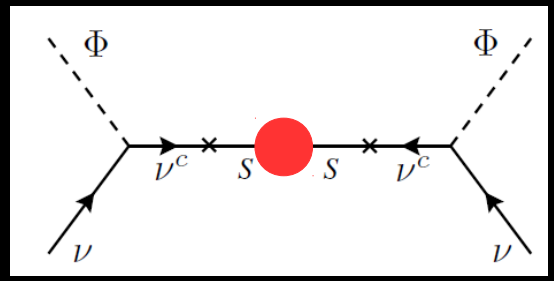


Phys.Rev.D 101 (2020) 115030

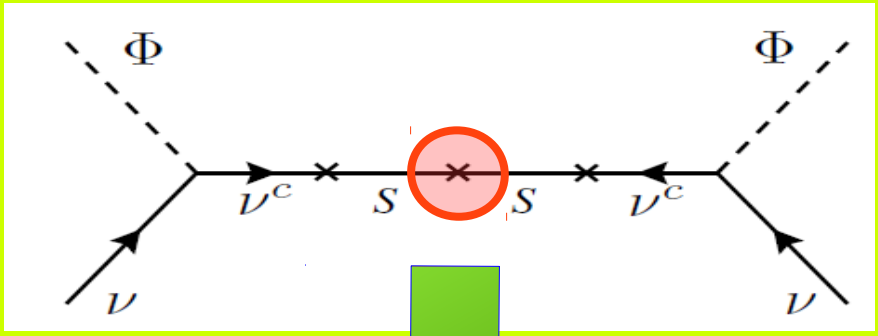
2009.10116 (JHEP) & 2103.02670

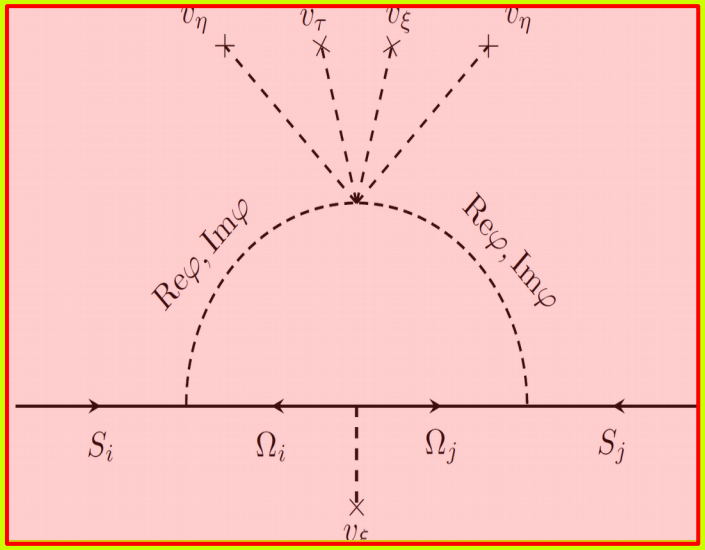
SM seesaw ➡ any number of RH singlet nus

- **MISSING PARTNER SEESAW** (3,2) (3,1) scoto-seesaw schemes
  Barreiros' talk
- **LOW-SCALE SEESAW (3,6)**
  Mohapatra-Valle 86
  Akhmedov et al PRD53 (1996) 2752
  PLB368 (1996) 270
  Malinsky Romao JV PRL95(2005)161801 ...



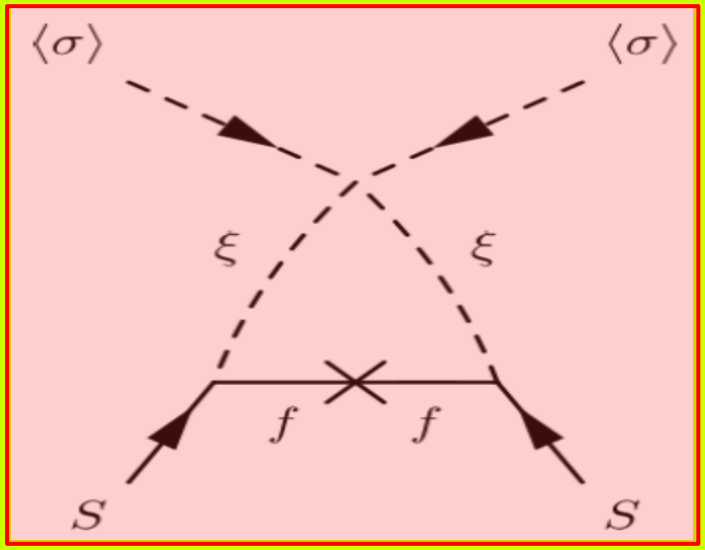
doubly protected low scale seesaw





radiative inverse seesaw

Cárcamo Hernández et al JHEP 1902 (2019) 065

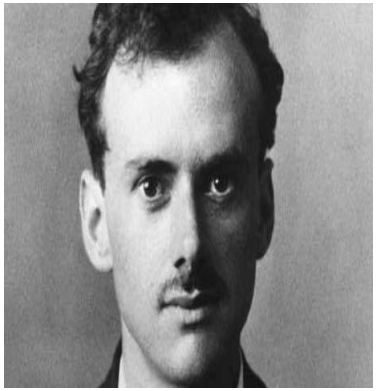


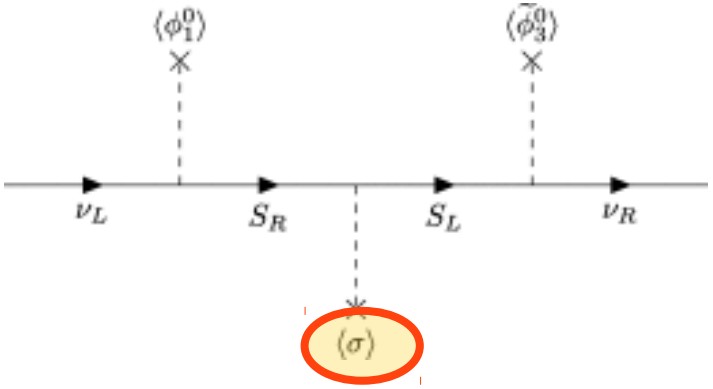
scotogenic inverse seesaw

arXiv:1907.07728 & 2012.05189 (JHEP)

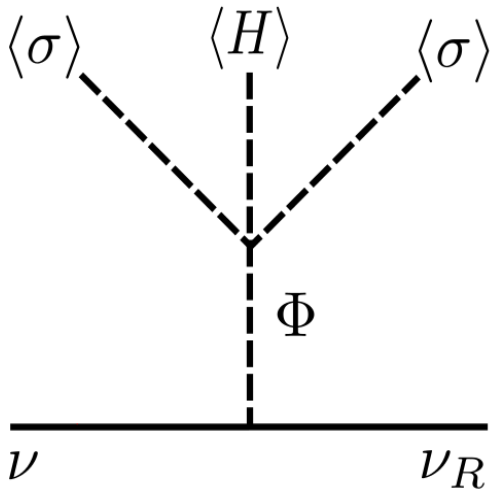
See also Bazzocchi et al 0907.1262, Ernest Ma 0904.4450, Baldes, Bell, Petraki, Volkas 1304.6162

seesawing a la





Type I



Type II

symmetry protects small neutrino mass + Diracness

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012

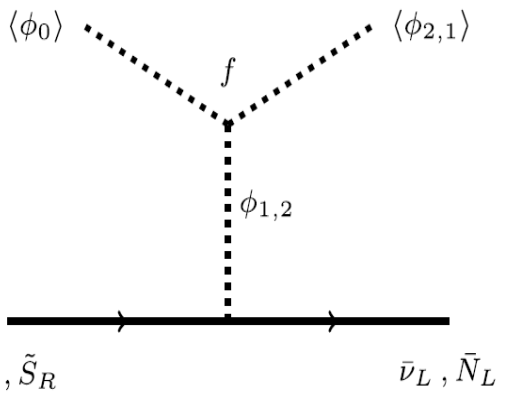
Peccei-Quinn symmetry

$$m_\nu^D \simeq \frac{y^{\nu_1}(y^S)^{-1}(y^{\nu_2})^T}{\sqrt{2}}\, v_{(W)} \frac{}{v_\sigma}$$

SU3L

PQ

Physics Letters B 810 (2020) 135829



Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

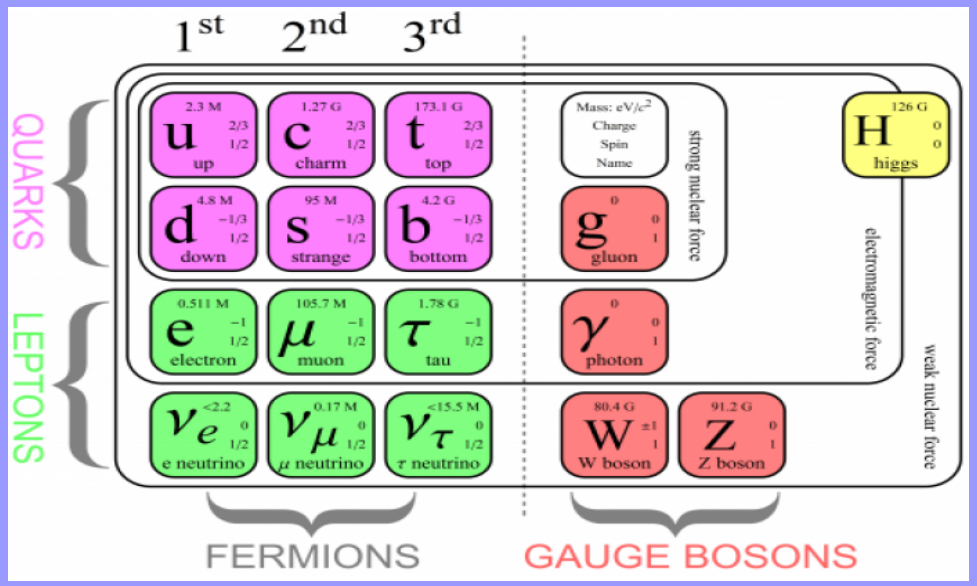
Phys.Rev. D98 (2018) 035009

Phys.Lett. B781 (2018) 122-128

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

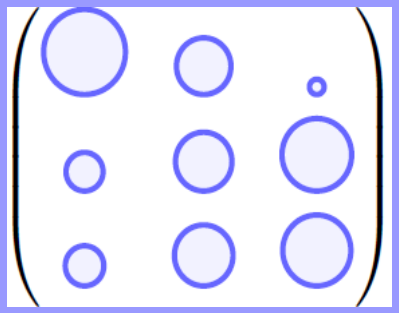
Phys.Lett. B755 (2016) 363-366

SM lacks an organizing principle to understand flavor

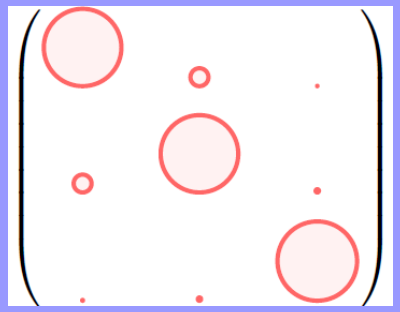


flavour legacy of oscillations

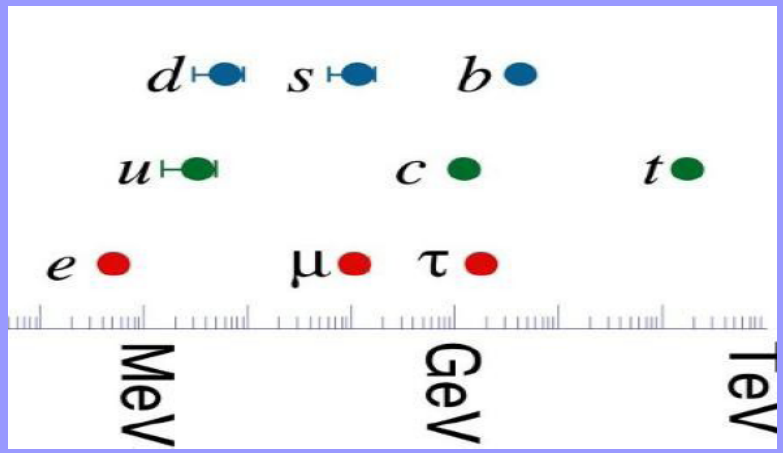
Q/L mixing pattern



versus



Q/L mass hierarchies



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
Reig, JV, Wilczek	Phys.Rev. D98 (2018) 095008

Golden Q-L mass relation

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

Warped flavour dynamics

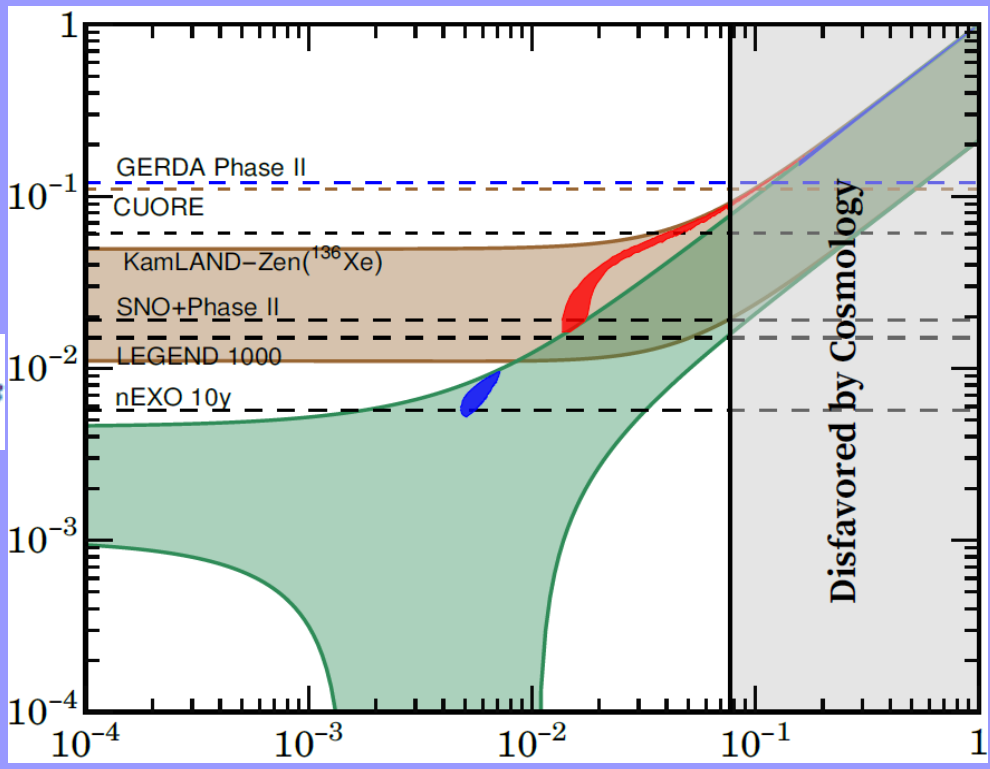
Randall-Sundrum Phys.Rev.Lett. 83 (1999) 3370

- **mass hierarchies from geometry**

  Arkani-Hamed & Schmaltz hep-ph/9903417

- **mixing angles from family symmetry**

T' predictions

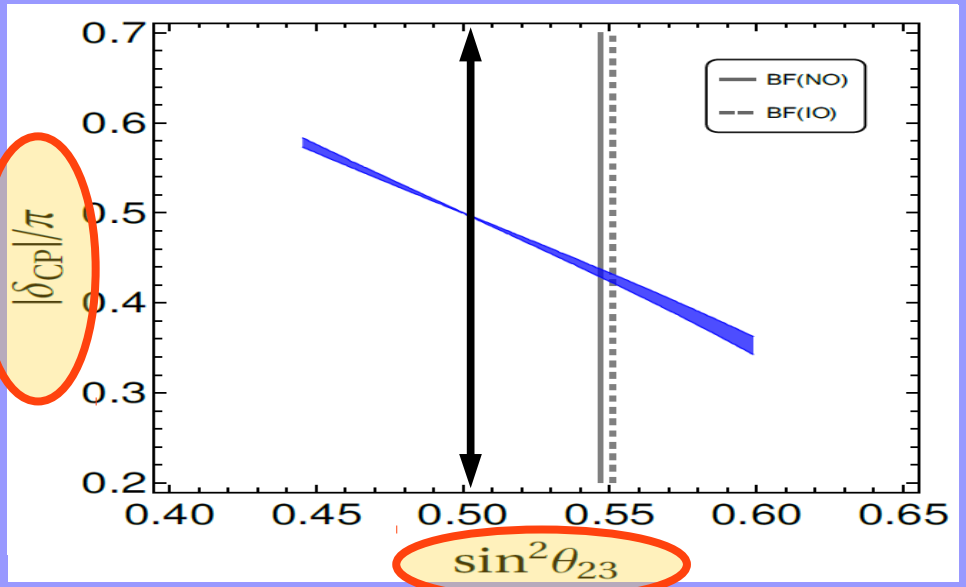


$$\cos^2\theta_{12}\cos^2\theta_{13} = \frac{2}{3}$$

From Chen et al 2003.02734

Phys. Rev. D 102, 095014 (2020)

$$\cos\delta_{CP} = \frac{(3\cos 2\theta_{12} - 2)\cos 2\theta_{23}}{3\sin 2\theta_{23}\sin 2\theta_{12}\sin\theta_{13}}$$

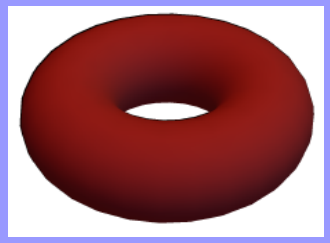


See also Chen et al
JHEP01(2016)007
Phys. Rev. D95 (2017) 095030
Phys.Lett. B771 (2017) 524

family symmetry from orbifolding

Phys.Lett.B 801 (2020) 135195

$$\mathcal{M} = \mathbb{M}^4 \times \left(\mathbb{T}^2/\mathbb{Z}_2\right)$$



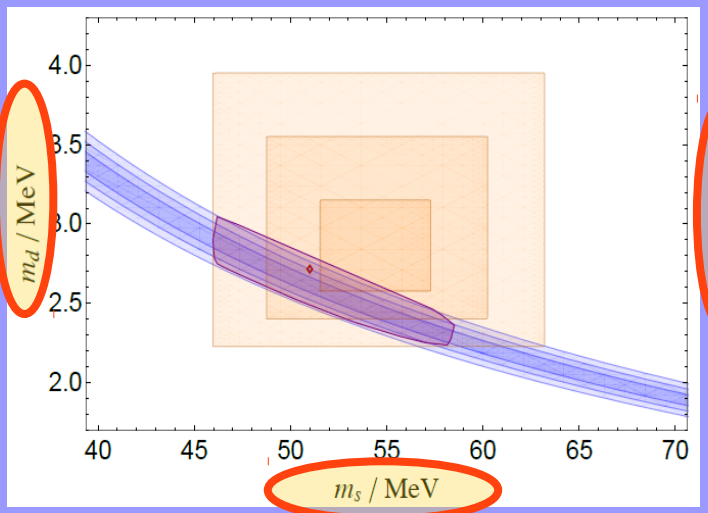
A4 family symmetry inherited from extra-dim

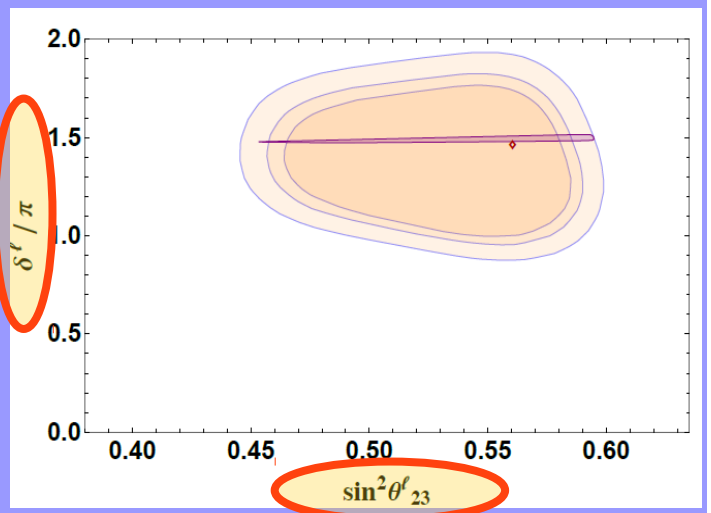
Golden Q-L relation

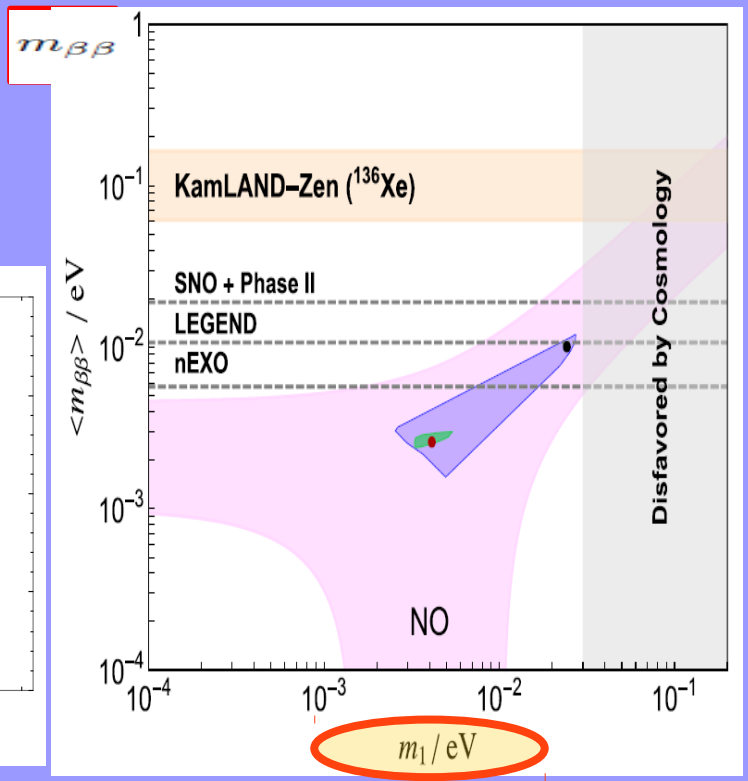
$$\frac{m_\tau}{\sqrt{m_\mu m_e}} \approx \frac{m_b}{\sqrt{m_s m_d}}$$

Sign of CP phase!

Phys.Rev.D 101 (2020) 11, 116012







Good global fit of all flavor observables

Dark Matter incorporated

Anda, Antoniadis et al JHEP 10 (2020) 190

what comes next

- **bright experimental future:**

  CP programme, oscillation robustness/unitarity tests ...

  neutrinoless double-beta decay & Majorana phase determination

  colliders may discover NHL mediators through LFV !

- **neutrinos at the center of particle physics :**

  neutrinos and flavor
  neutrinos and strong CP problem
  neutrinos and unification
  dark matter as neutrino mass mediator
  neutrino Diracness and DM stability
  neutrinos and LFV