neutrinos and search for fundamental symmetries

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ASTROPARTICLES
Astroparticles and High Energy Physics Group

NCTS Annual Theory Meeting 2020: Particles, Cosmology and Strings (December, 2020)

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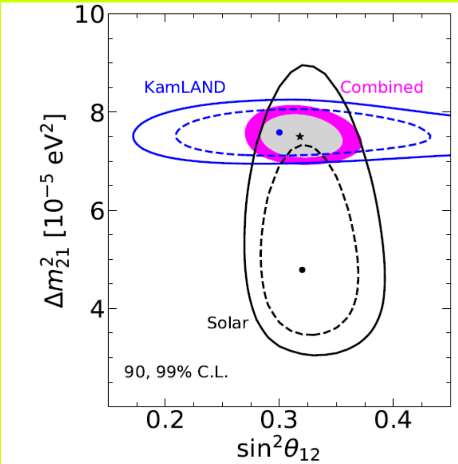
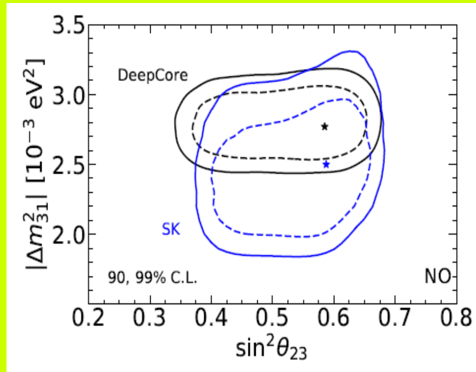
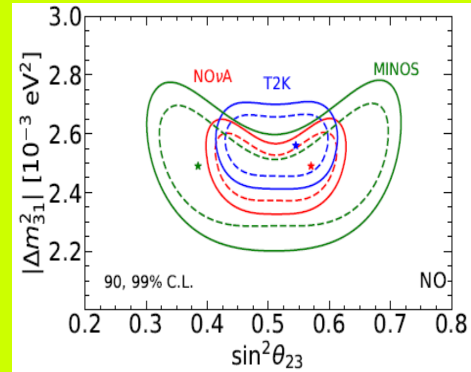
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
GENERALITAT VALENCIANA Conselleria d'Educació, Investigació, Cultura i Esport

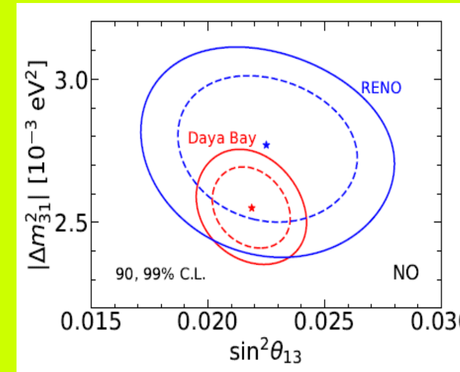
neutrino oscillations 2020

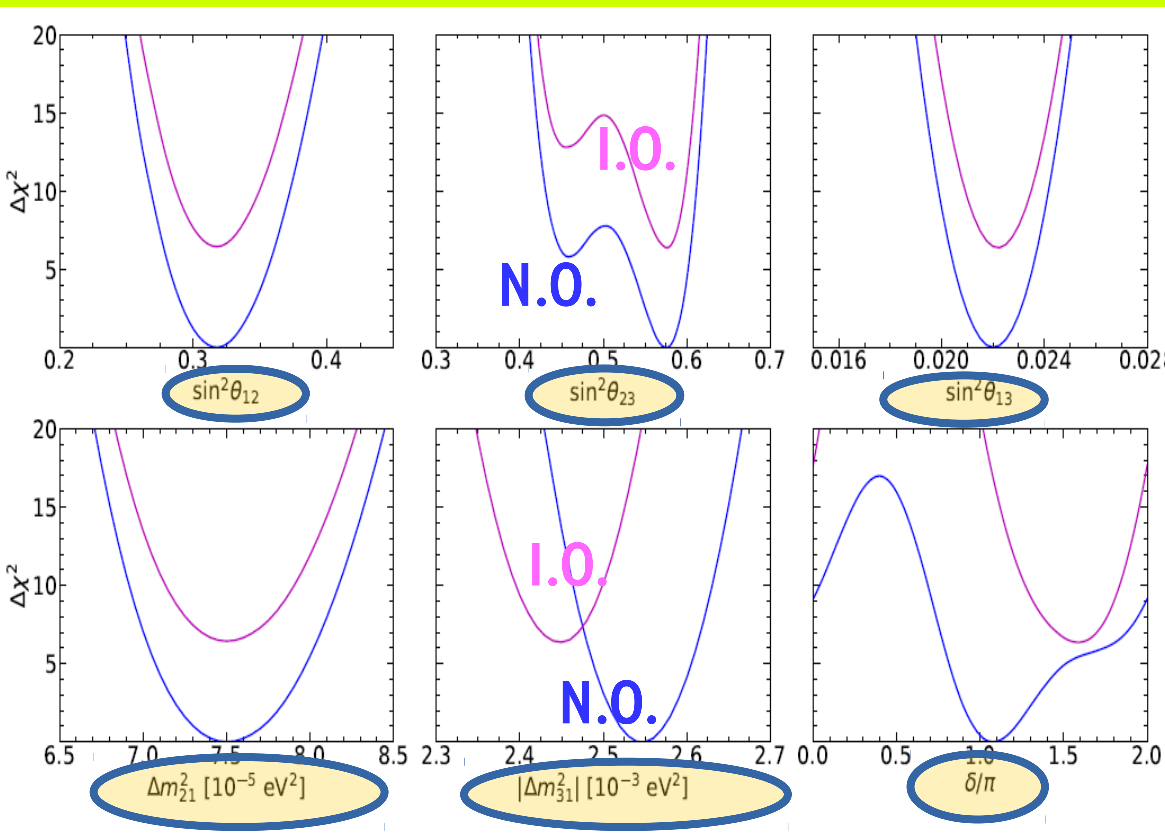
Post-Neutrino2020











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

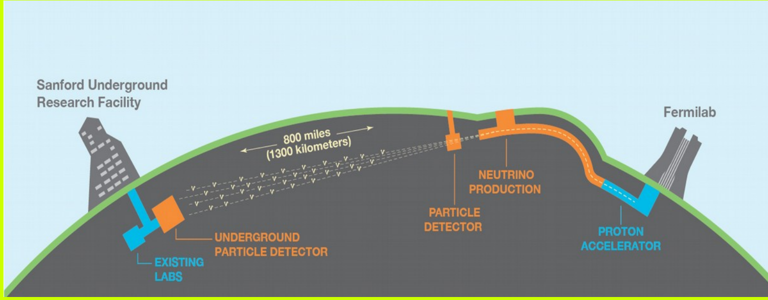
Room for improvement!!
CP, ATM octant & ordering

P.F. de Salas et al 2006.11237

https://globalfit.astroparticles.es/

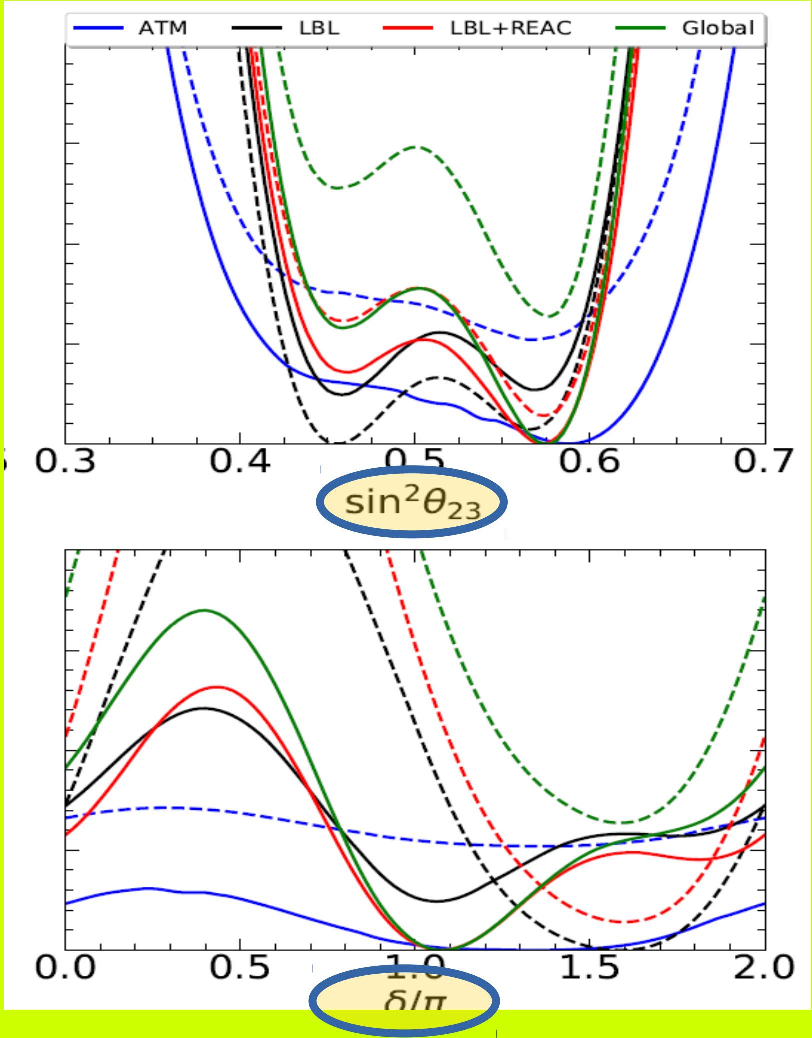
@jwvalle 2

Future leptonic CP violation



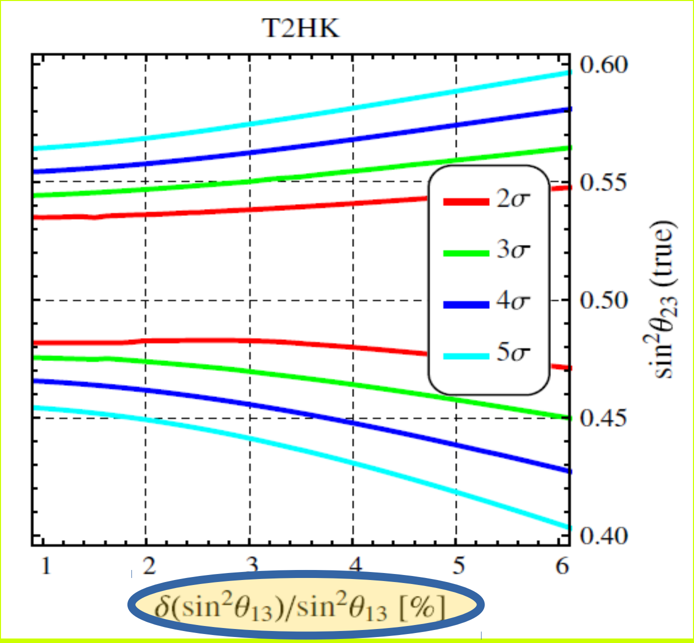
- CP phase
- atm octant

From P.F. de Salas et al 2020 See also 1811.07040



from Phys.Rev.D96 (2017) 011303(R)

See also Phys.Rev. D97 (2018) 095025



2, 3, 4 and 5σ "octant-blind" regions remain

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) 644-652

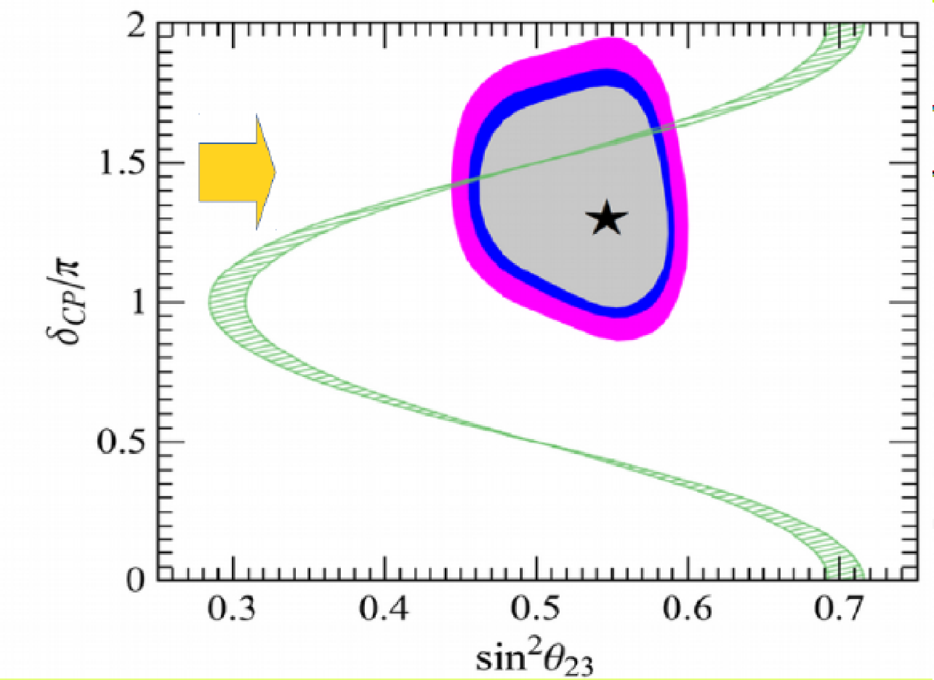
Phys.Rev. D94 (2016) 033002

JHEP 1807 (2018) 077

Phys.Lett. B792 (2019) 461-464

Phys.Rev. D99 (2019) 075005

predicting CP



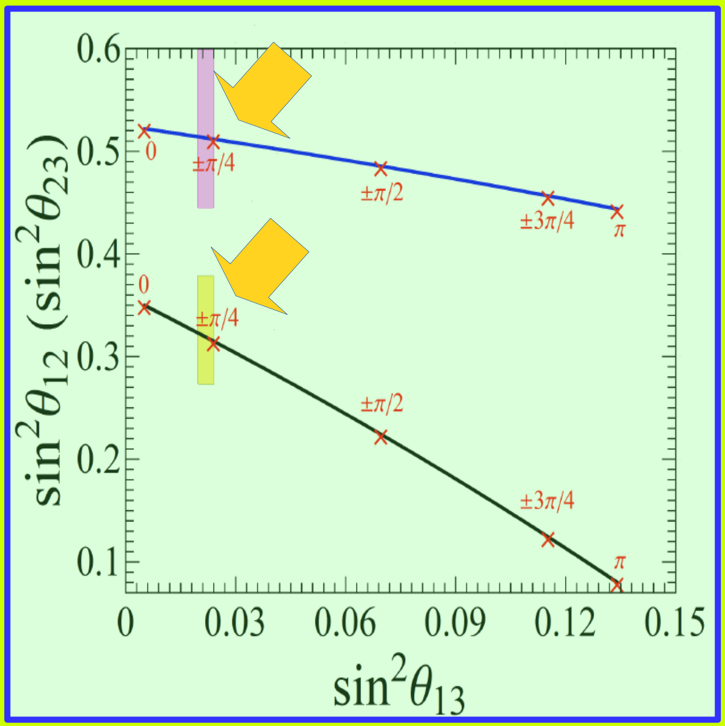
Bi-Large lepton mixing pattern

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

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

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

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



Phys.Lett. B792 (2019) 461

predicting solar + atm

for “softer” version of Bi-Large see

Phys.Lett.B 796 (2019) 162

unitarity as seesaw probe

J.V. Phys.Lett. B199 (1987) 432

Miranda & J.V. Nucl.Phys. B908 (2016) 436

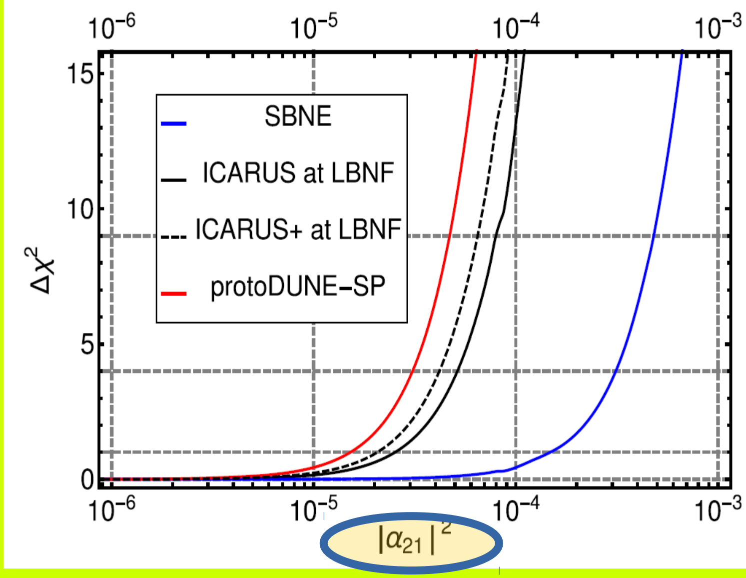
Escrihuela et al, Phys.Rev. D92 (2015) 053009

New J. Phys. 19 (2017) 093005

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

PRD97 (2018) 095026

	One parameter (1 d.o.f.)		All parameters (6 d.o.f.)	
	90% C.L.	3σ	90% C.L.	3σ
Neutrinos only				
$\alpha_{11}>$	0.98	0.95	0.96	0.93
$\alpha_{22}>$	0.99	0.96	0.97	0.95
$\alpha_{33}>$	0.93	0.76	0.79	0.61
$\lvert\alpha_{21}\rvert<$	1.0×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	3.6×10^{-2}
$\lvert\alpha_{31}\rvert<$	4.2×10^{-2}	9.8×10^{-2}	9.0×10^{-2}	1.3×10^{-1}
$\lvert\alpha_{32}\rvert<$	9.8×10^{-3}	1.7×10^{-2}	1.6×10^{-2}	2.1×10^{-2}



near measurements necessary for the DUNE programme

PRL **117**, 061804 (2016) PHYSICAL REVIEW LETTERS

New Ambiguity in Probing *CP* Violation in Neutrino Oscillations

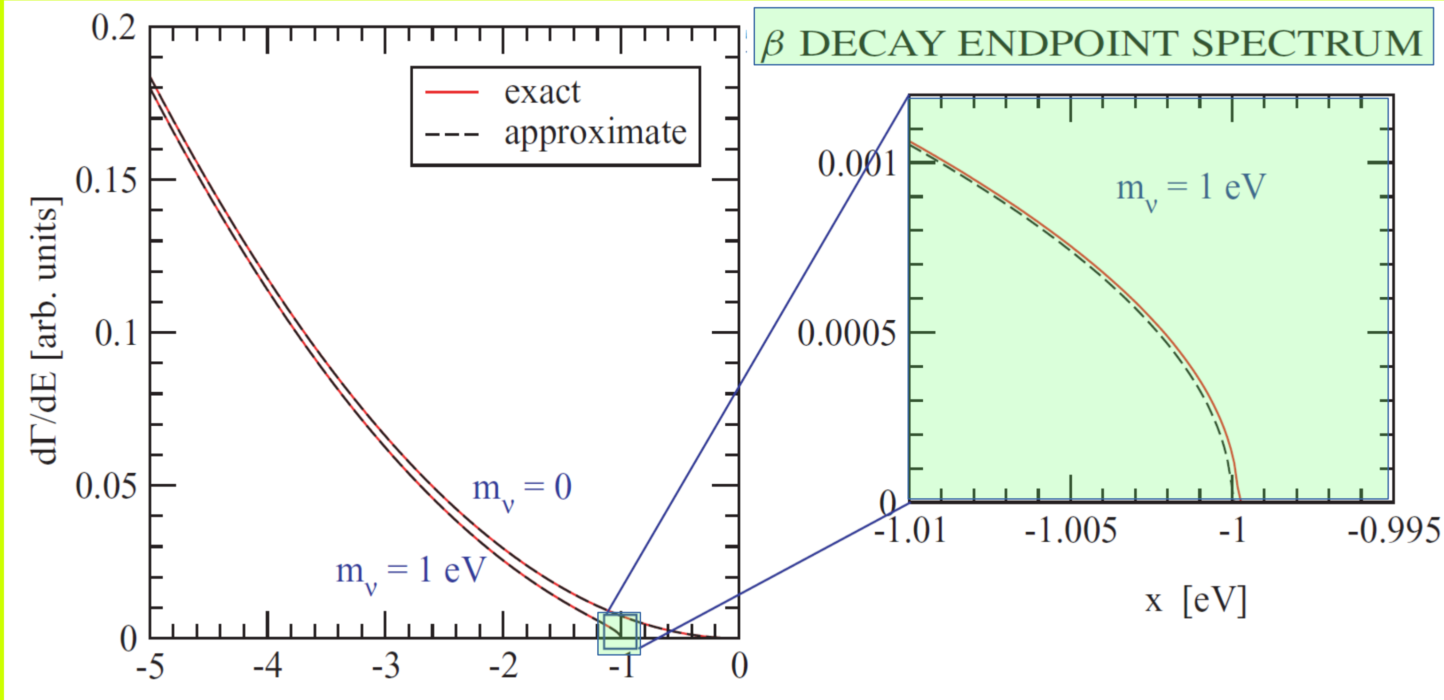
Miranda et al

Shao-Feng Ge et al

Phys.Rev. D95 (2017) 033005

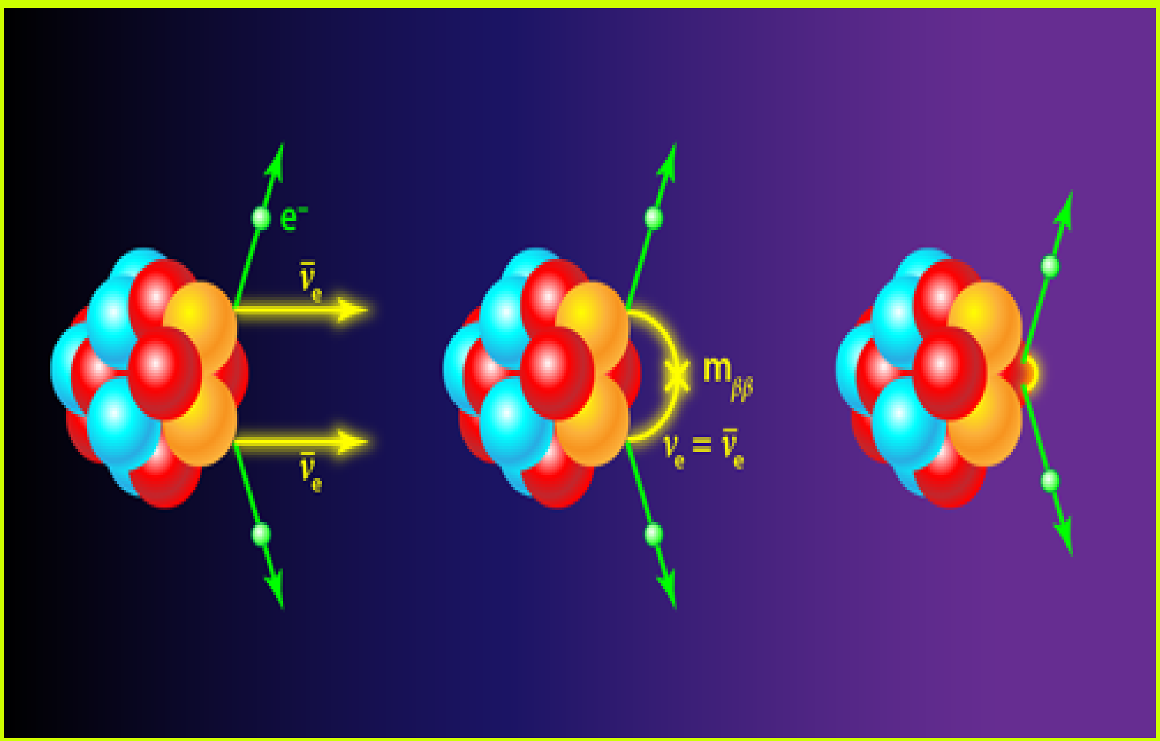
beta decays probe neutrino mass scale

KATRIN limit 1.1eV

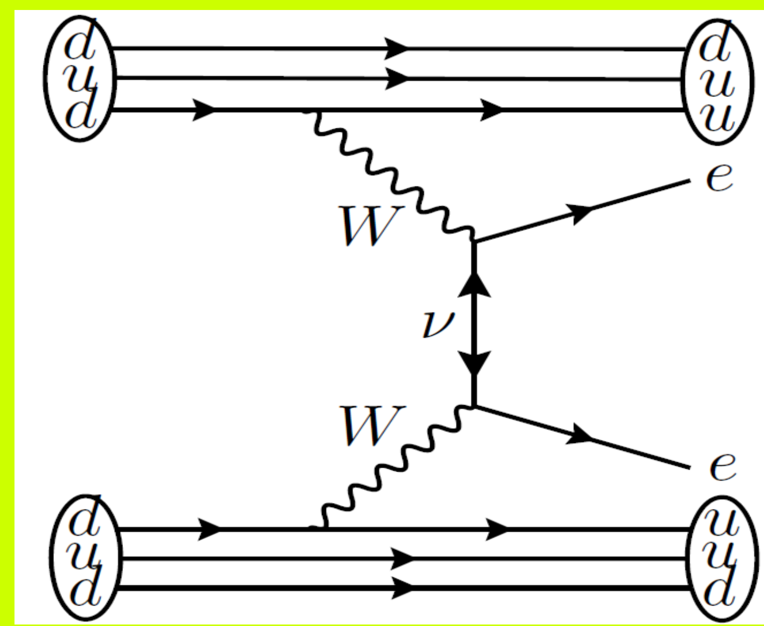


S.S. Masood et al, Phys.Rev. C76 (2007) 045501

double beta decays



A.S. Barabash arXiv:1104.2714



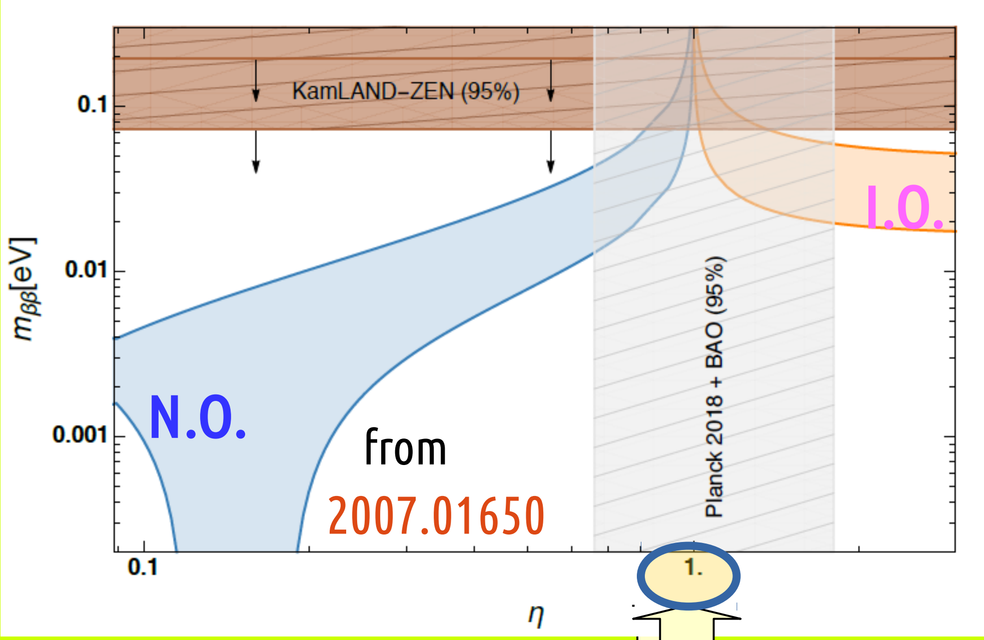
0-nu DBD $0\nu\beta\beta$

$$\left|\sum_j U_{ej}^2 m_j\right| = \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{2i\phi_{12}} + s_{13}^2 m_3 e^{2i\phi_{13}}\right|$$

Schechter & JV PRD22 (1980) 2227

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

- **Quasi-degenerate nearly excluded**
  Babu, Ma, Valle 2003
  Lattanzi, Gerbino, Freese, Kane, Valle 2020

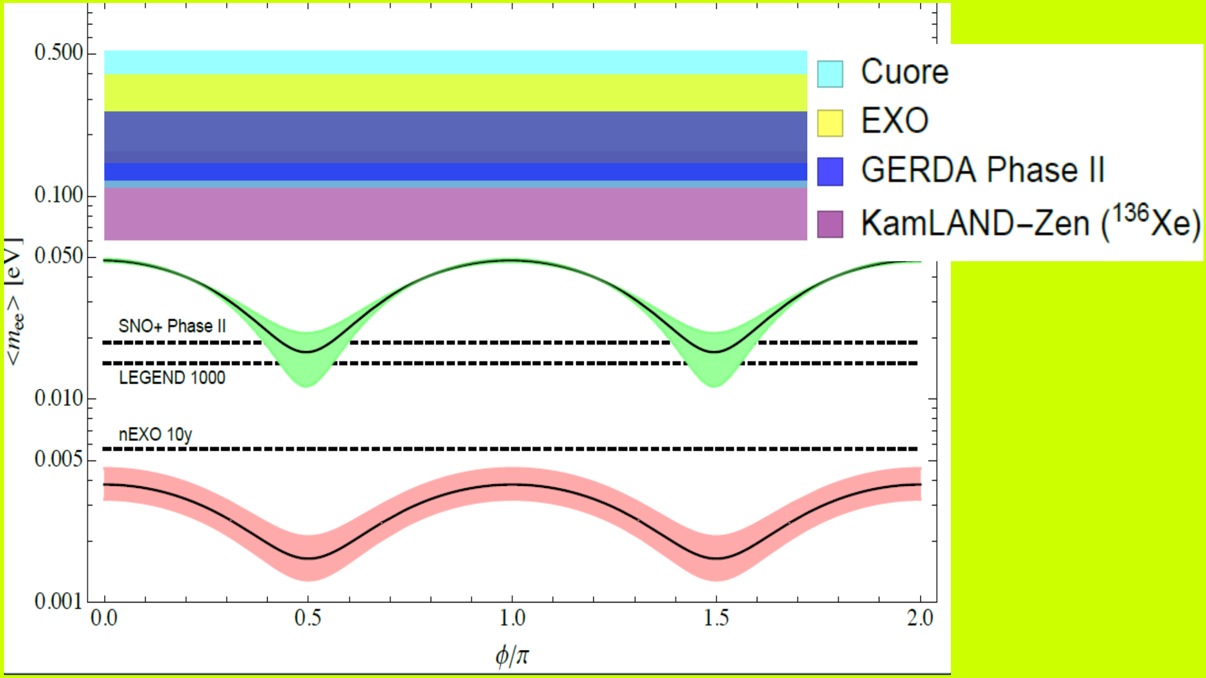


degeneracy parameter

- **one-massless**

JHEP 1310 (2013) 149
Phys.Lett.B 789 (2019) 132
Phys.Lett. B790 (2019)303

$m_{\beta\beta}$



flavor sensitivity neutrinoless doublebeta decay

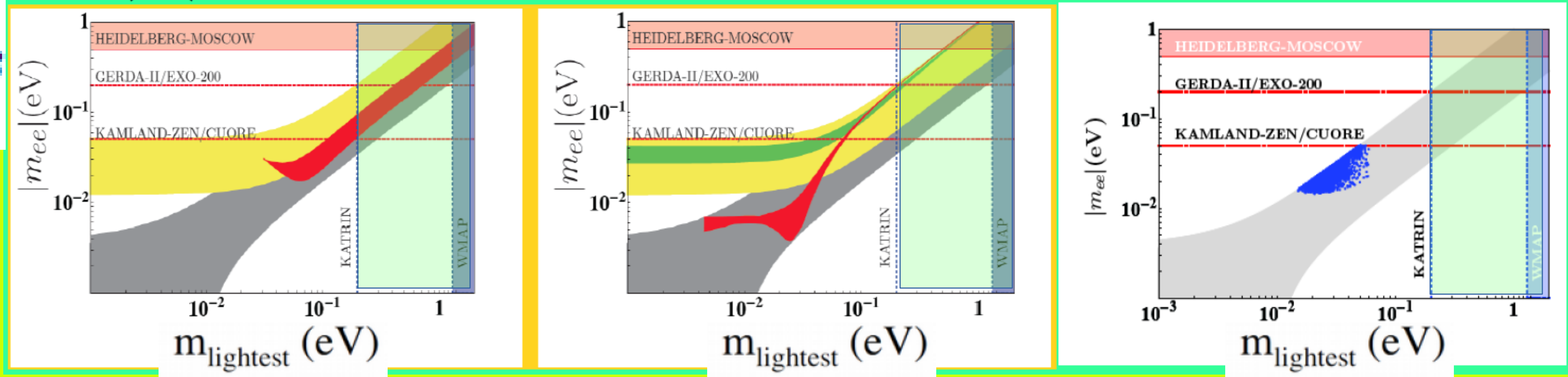
lower bounds even for normal ordering

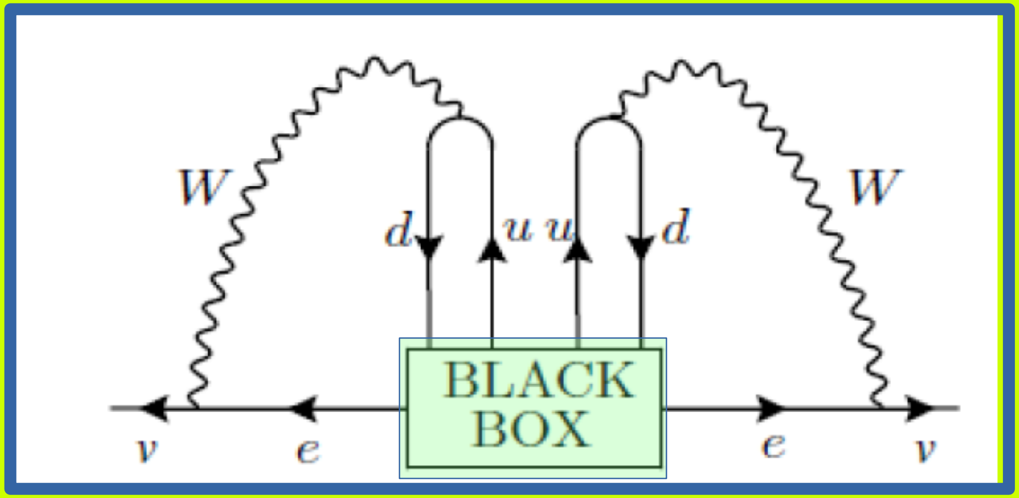
$m_{\beta\beta}$

Dorame et al NPB861 (2012) 259-270

Dorame et al PhysRevD.86.056001

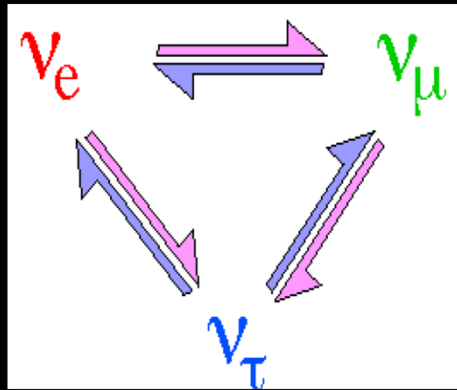
King et al Phys. Lett. B 724 (2013) 68





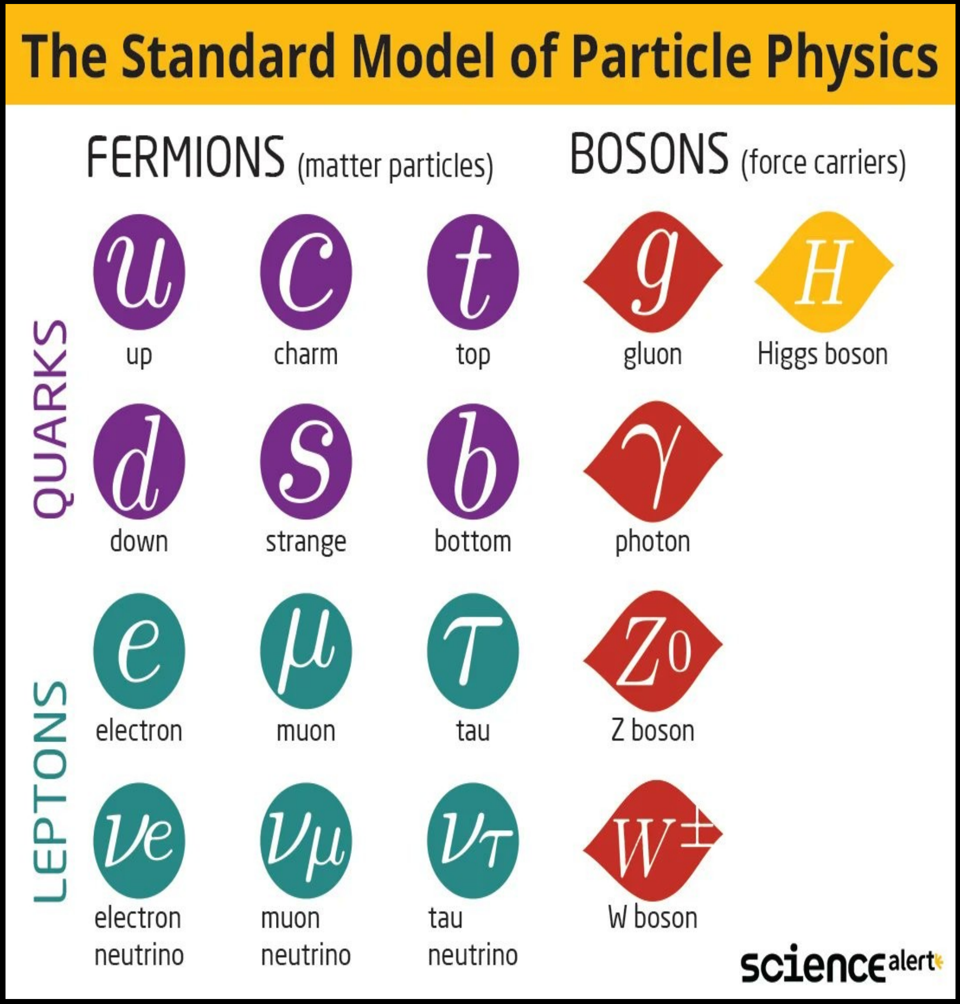
Schechter, Valle 82

Lindner et al JHEP 1106 (2011) 091



the discovery of oscillations brings neutrinos to the center of particle physics

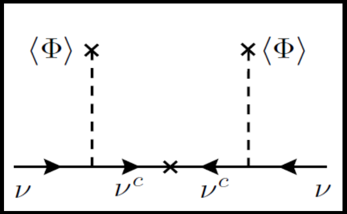
addressing the dynamical origin of small neutrino mass touches the the heart of the theory



besides neutrino mass there are many other issues in particle physics & cosmology for which neutrinos may provide key input

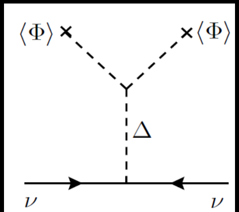
search for underlying symmetries

dynamical 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

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

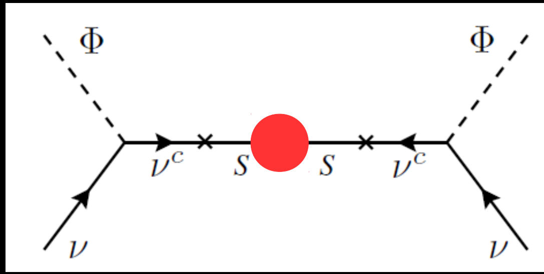
Phys.Rev.D 101 (2020) 115030

SM gauge group ➡ any number m of singlet R's

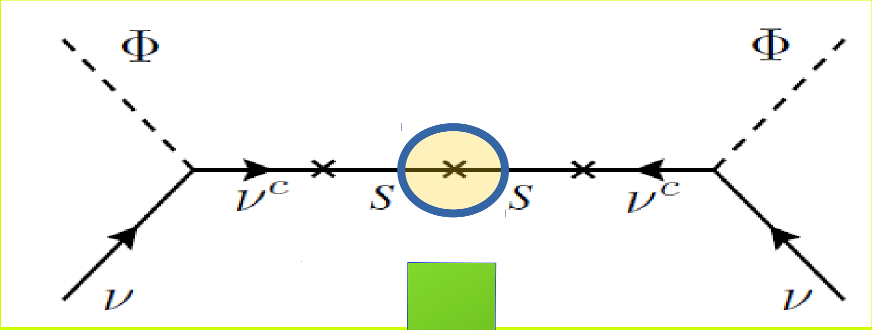
- **MISSING PARTNER SEESAW** (3,2) (3,1)+

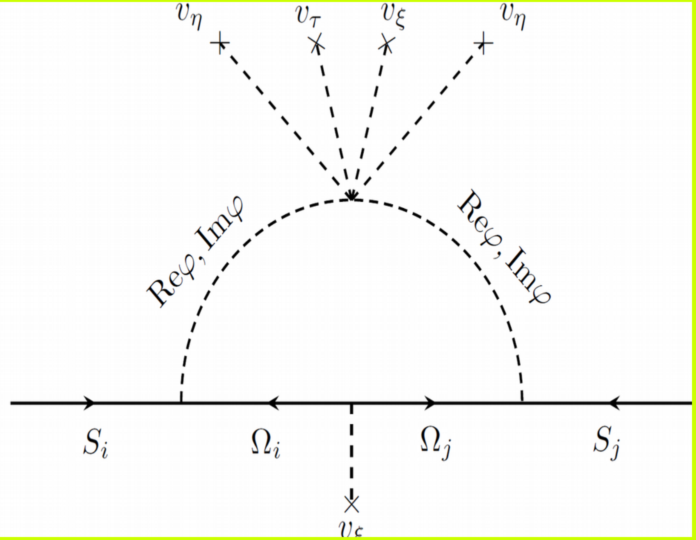
- **LOW-SCALE SEESAW (3,6)**

Mohapatra-Valle 86
Akhmedov et al PRD53 (1996) 2752
Malinsky et al PRL95(2005)161801



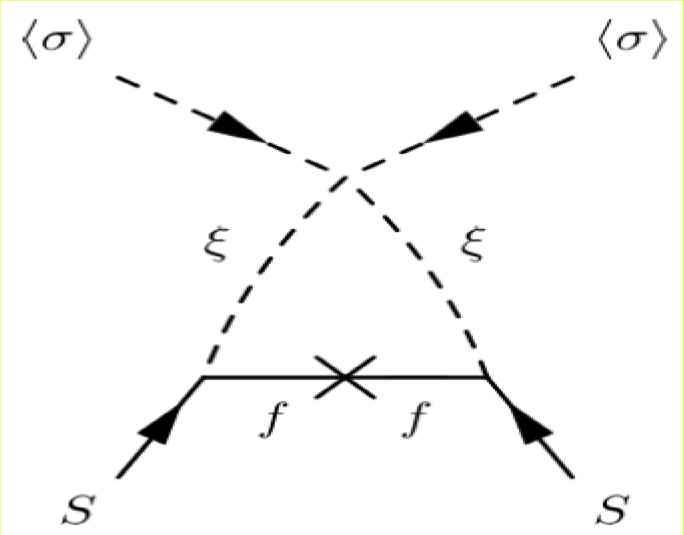
doubly protected low scale seesaw





radiative inverse seesaw

:Cárcamo Hernández et al JHEP 1902 (2019) 065

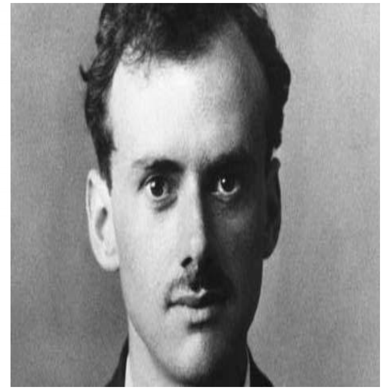


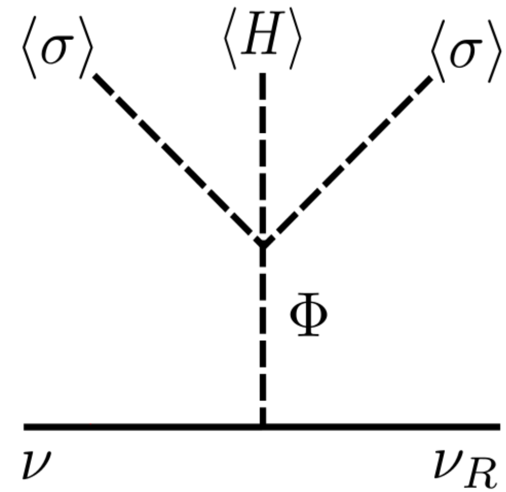
scotogenic inverse seesaw

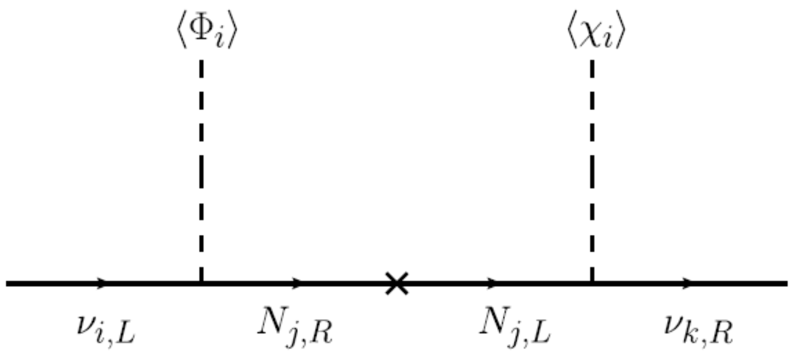
From arXiv:1907.07728

See also Bazzocchi et al 0907.1262 Ma 0904.4450 Baldes et al 1304.6162

Seesawing a la







Type I

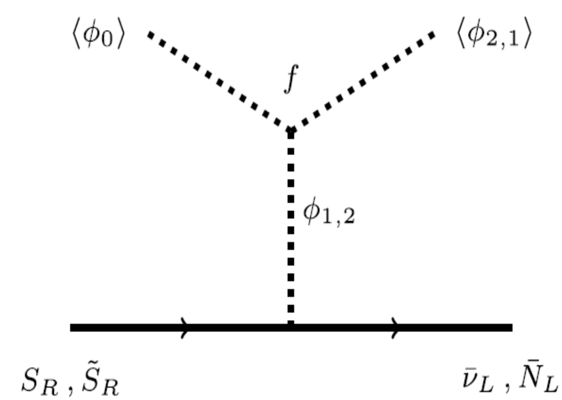
Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

Type II

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



symmetry protects

small neutrino mass

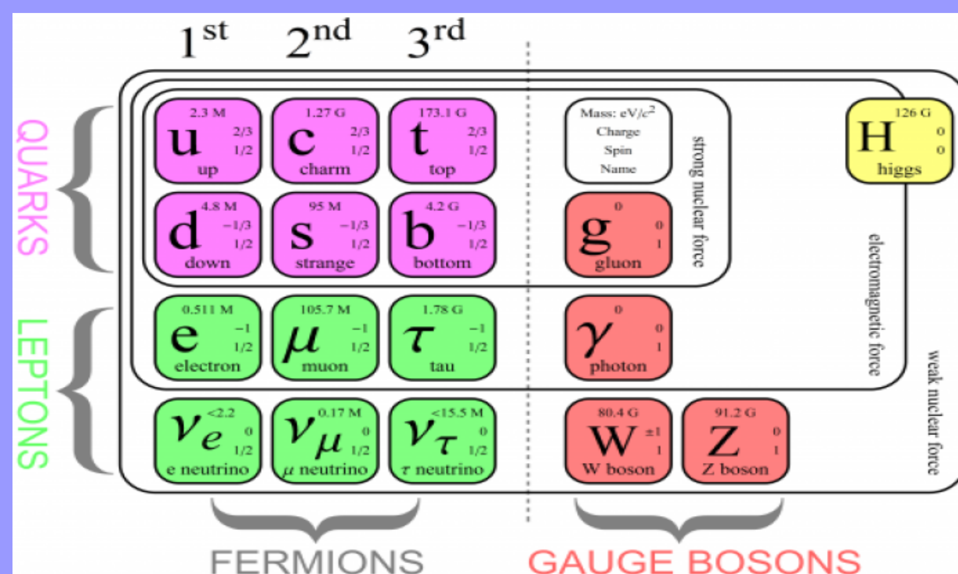
Phys.Rev. D98 (2018) 035009

Phys.Lett. B781 (2018) 122-128

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

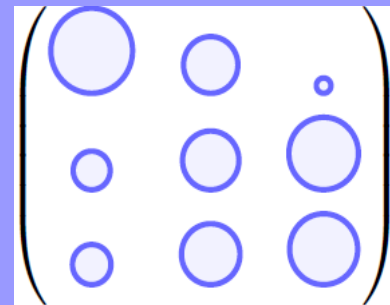
Phys.Lett. B755 (2016) 363-366

SM lacks an organizing principle to understand flavor

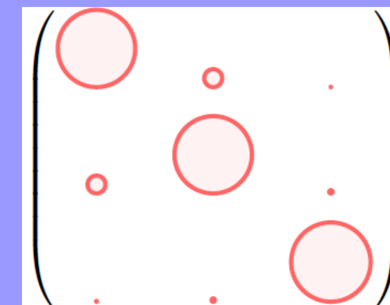


flavour legacy of oscillations

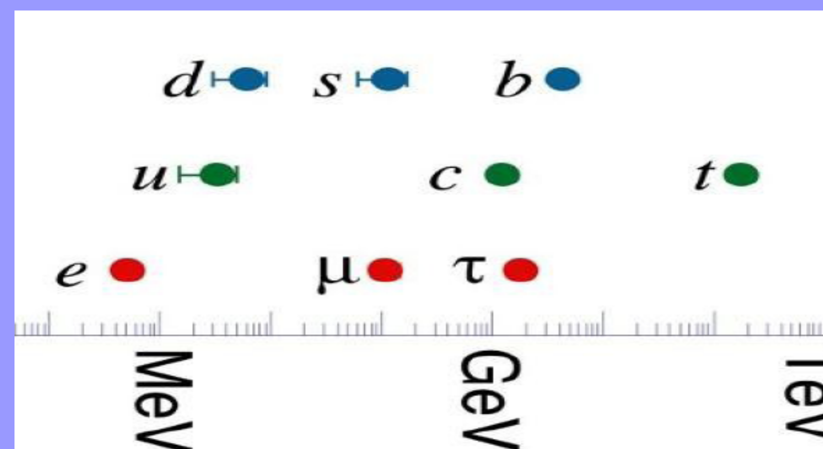
Q/L mixing pattern



versus



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

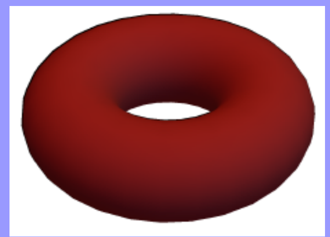
Golden Q-L mass relation

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

family symmetry from orbifolding

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

Phys.Lett.B 801 (2020) 135195

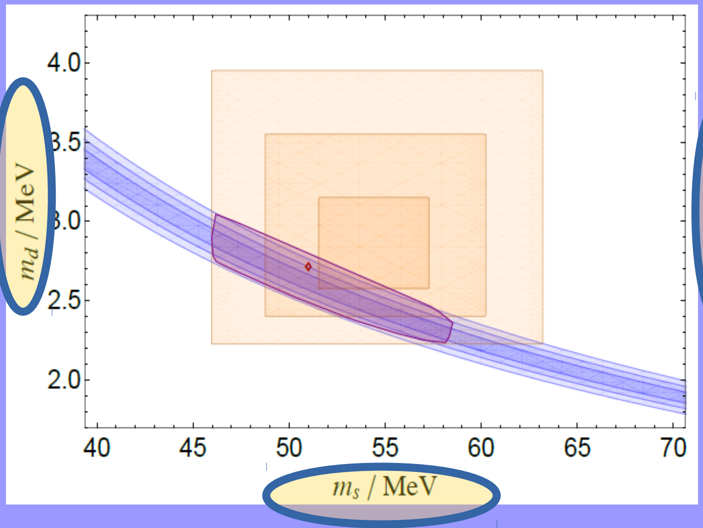


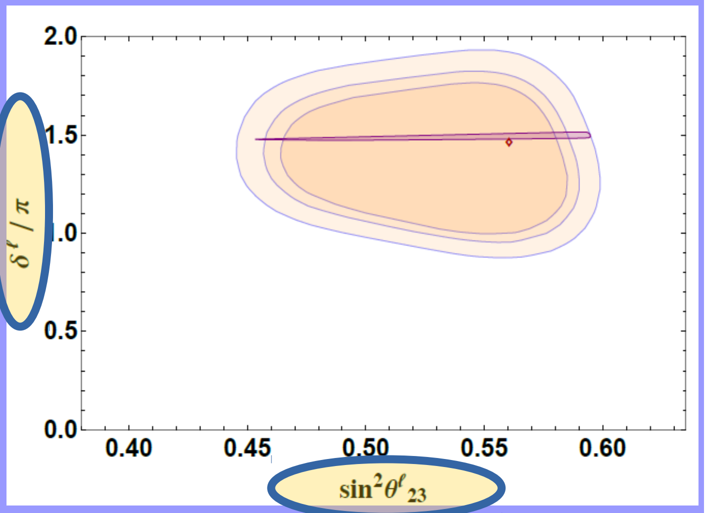
flavor symmetry
from extra-dim

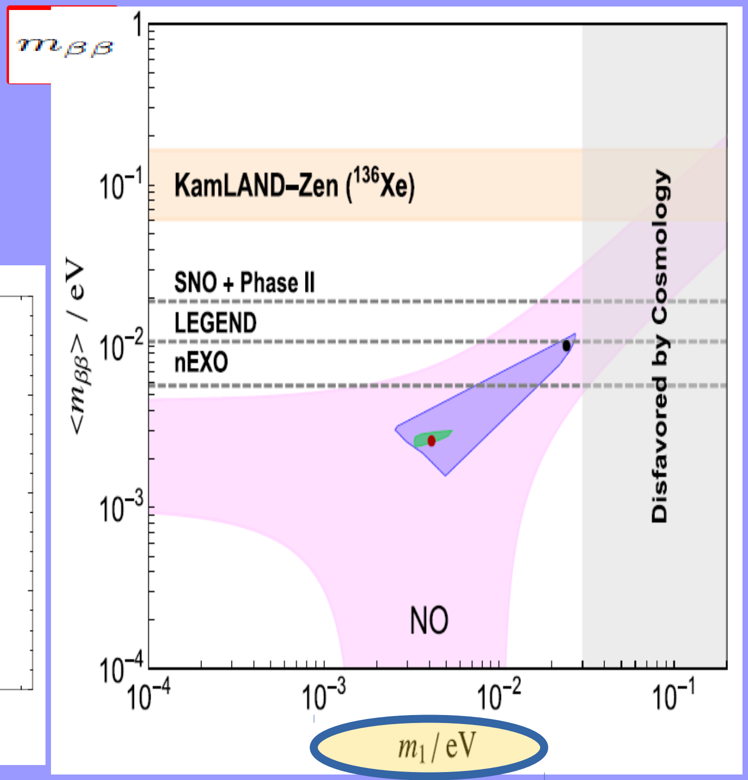
Golden Q-L relation

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

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







Good global fit of all flavor observables

Anda, Antoniadis et al
JHEP 10 (2020) 190

@jwvalle 16

warped flavour dynamics

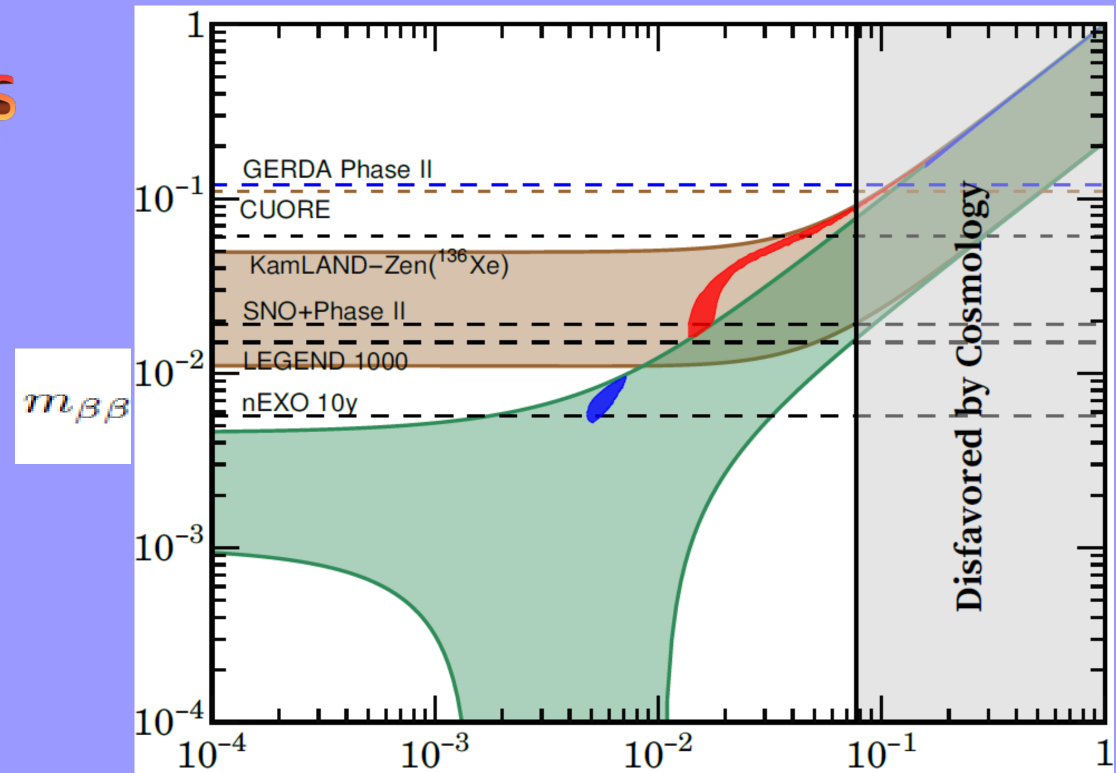
- angles related by T’ symmetry

flavour & 0-nu DBD predictions

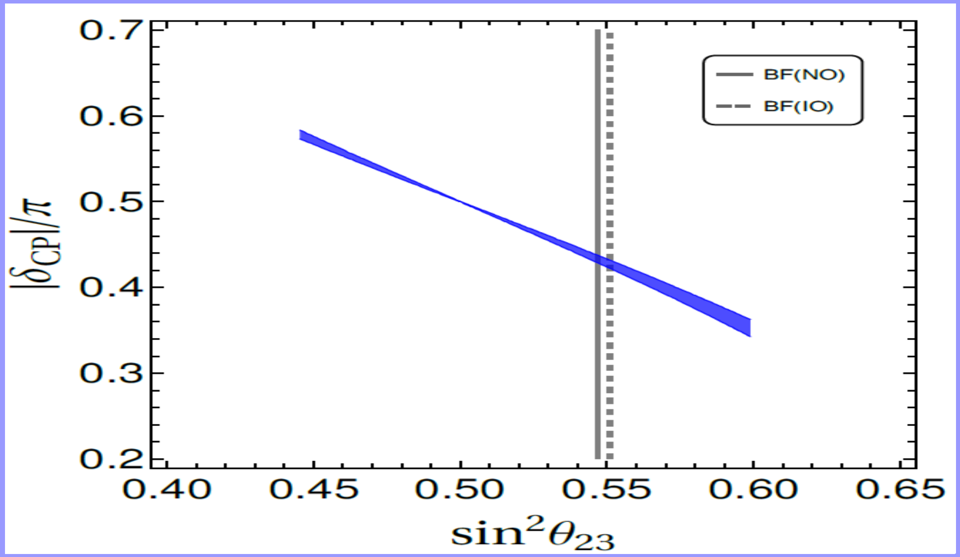
$$\cos^2\theta_{12}\cos^2\theta_{13} = \frac{2}{3}$$

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

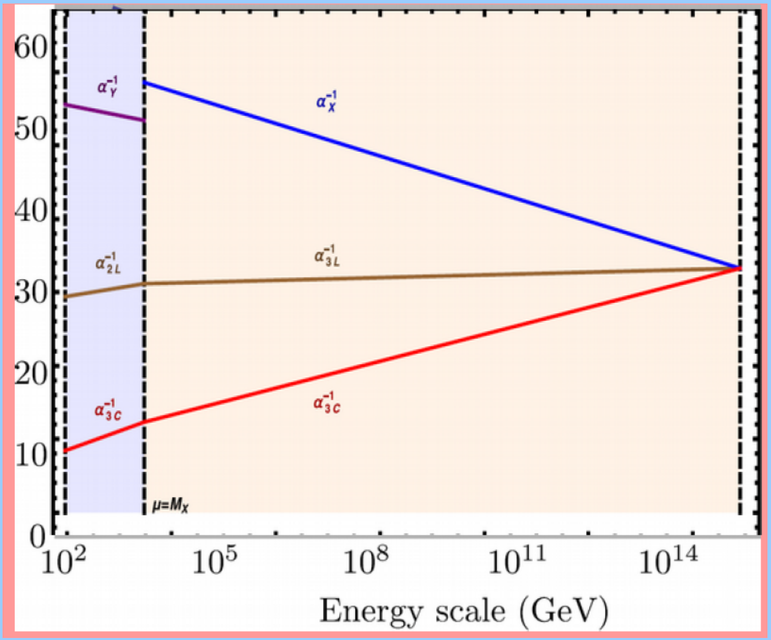
- mass hierarchies from geometry



From Chen et al 2003.02734



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



neutrinos & unification

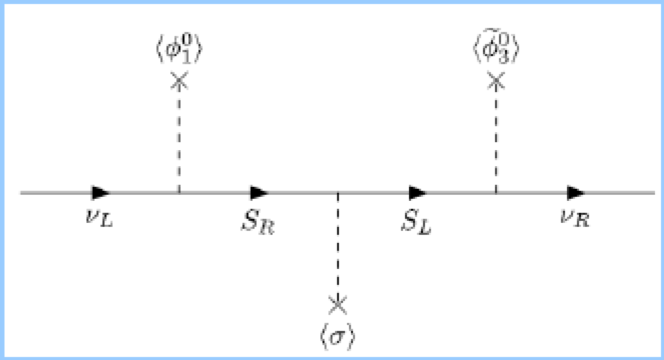
the physics responsible for neutrino masses may also induce gauge coupling unification

Boucenna et al Phys. Rev. D 91, 031702 (2015)

Deppisch et al Phys.Lett. B762 (2016) 432

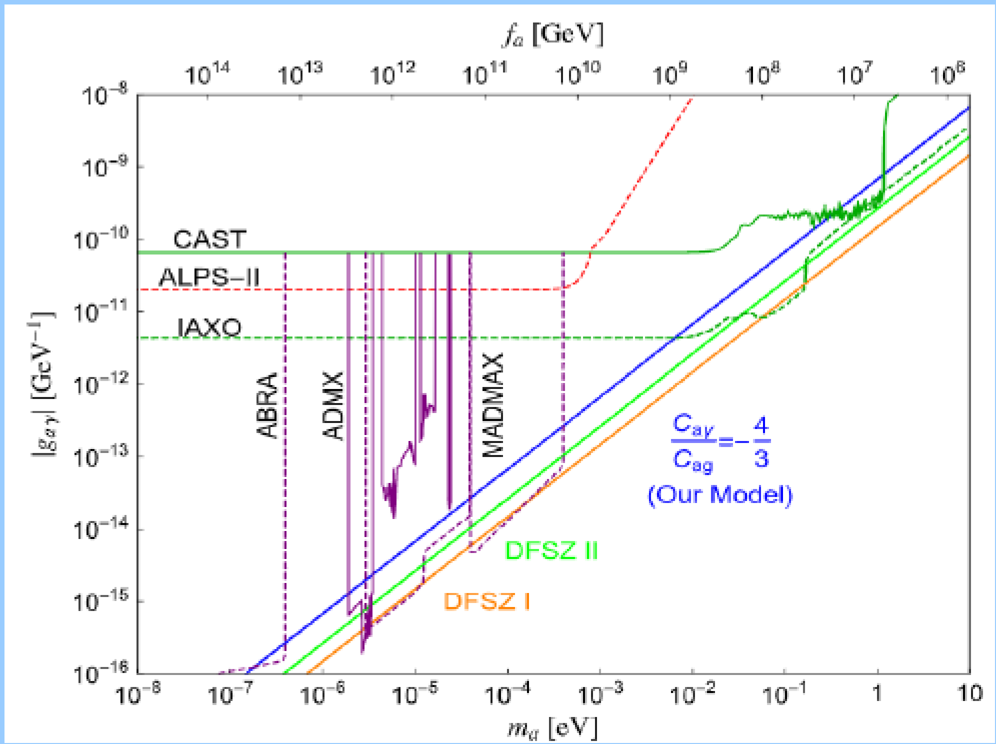
reloading the axion

- **why 3 families** PRD22(1980)738
- **Dirac seesaw neutrino mass**



$$m_\nu^D \simeq \frac{y^{\nu_1}(y^S)^{-1}(y^{\nu_2})^T}{\sqrt{2}}\,\frac{v_1 w}{v_\sigma}\,.$$

From *Physics Letters B 810 (2020) 135829*

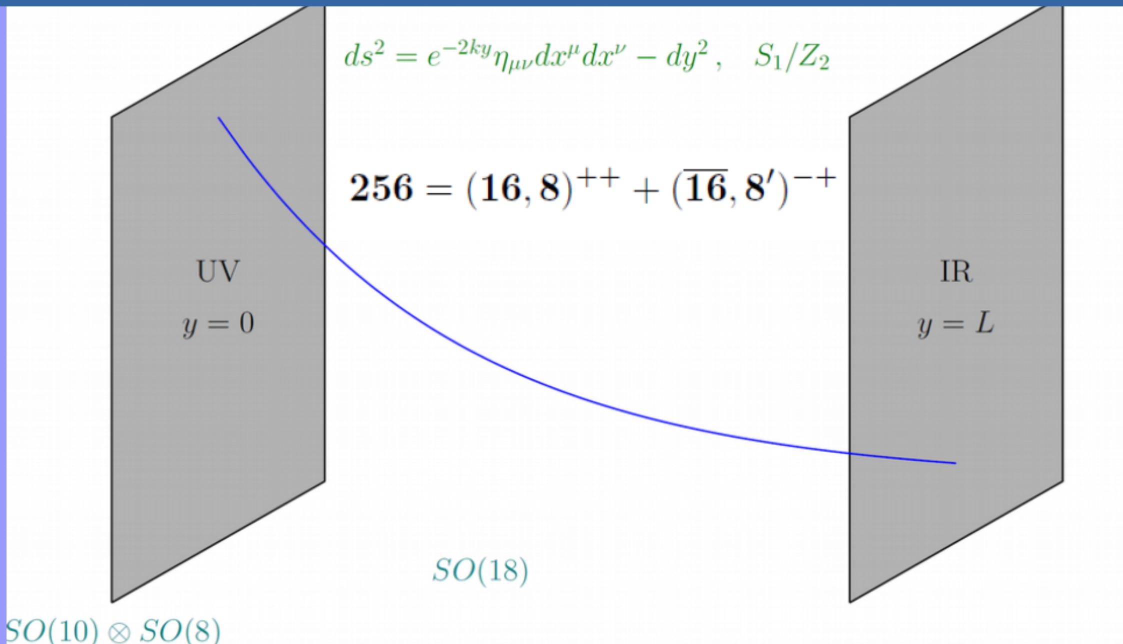


tree-level quark FCNC

New path to family unification

inspired by beauty of neutrinos in SO10

$$\mathbf{16} \to (\mathbf{3},\mathbf{2},1/6) + (\mathbf{1},\mathbf{2},-1/2) + (\bar{\mathbf{3}},\mathbf{1},1/3) + (\bar{\mathbf{3}},\mathbf{1},-2/3) + (\mathbf{1},\mathbf{1},1) + (\mathbf{1},\mathbf{1},0),$$



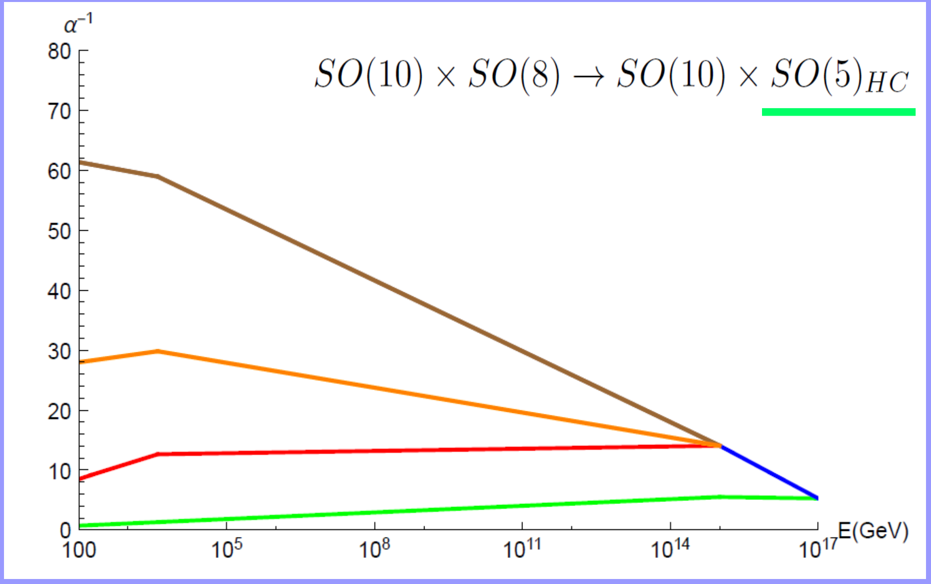
Reig, Valle, Vaquera-Araujo, Wilczek

Phys.Lett. B774 (2017) 667-670

unwanted chiral families bound by new hypercolor force above TeV

promote M4 to AdS5 & use orbifold BC to decouple mirrors

new spectroscopy



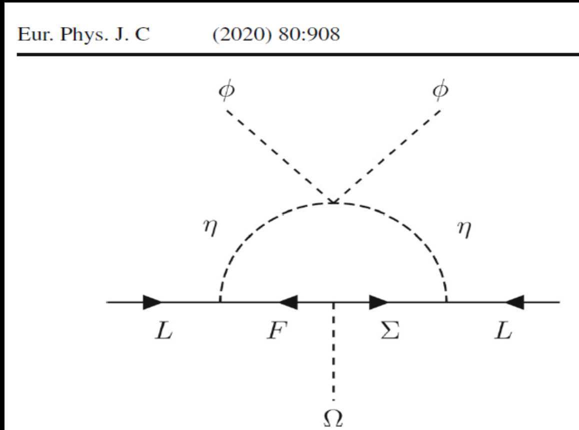
SO(3) family symmetry

Reig, JV, Wilczek

Phys.Rev. D98 (2018) 095008

	q_L	u_R	d_R	l_L	e_R	ν_R	Φ^u	Φ^d	Ψ^u	Ψ^d	σ	ρ
$SU(3)_c$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**2**	**2**	**2**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	0	0
$SO(3)_F$	**3**	**3**	**3**	**3**	**3**	**3**	**5**	**5**	**3**	**3**	**5**	**1**
$U(1)_{PQ}$	1	-1	-1	1	-1	-1	2	2	2	2	2	2

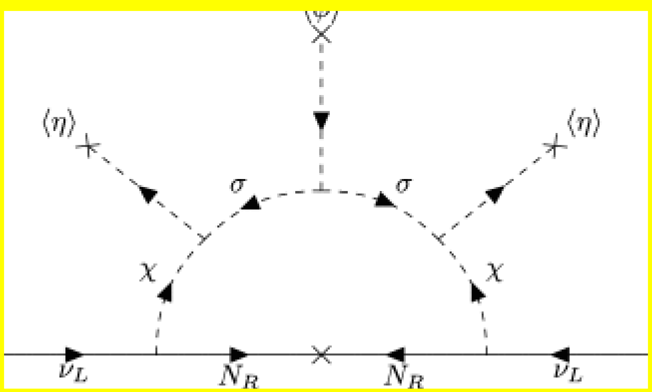
incorporating WIMP DM

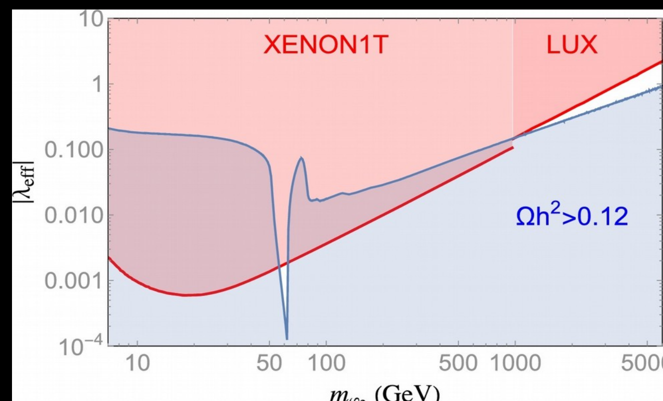


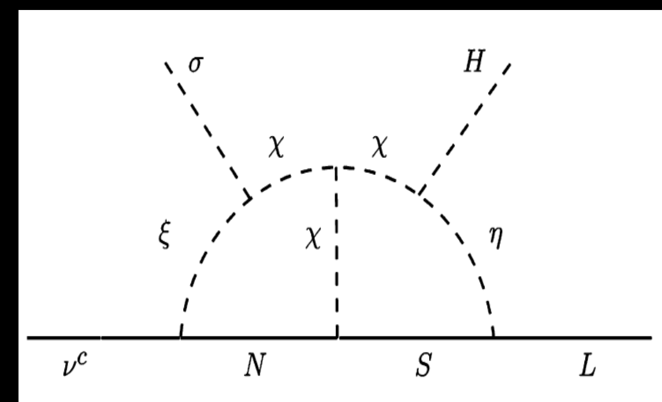
Dark Matter as neutrino mass mediator

E Ma 2006
Hirsch et al JHEP 1310 (2013) 149
Merle et al JHEP07 (2016) 013
Diaz et al JHEP08 (2017) 017; Avila et al 1910.08422
Rojas et al

stabilized by e.g. remnant gauge symmetry
Phys.Lett.B 798 (2019) 135013 & 2006.06009



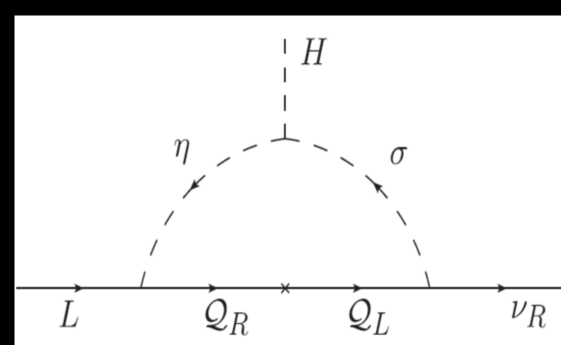




Bonilla et al PLB 762 (2016) 214-218

bound-state scotogenic
Phys.Rev.D 97 (2018) 11, 115032
Phys.Lett.B 790 (2019) 303-307

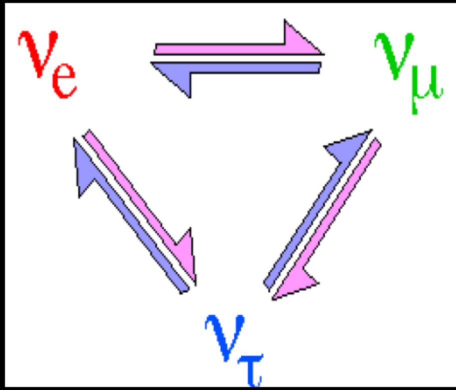
DM and nu-Diracness



Anda, Antoniadis et al
JHEP 10 (2020) 190

@jwvalle 20

Oscillation Legacy



- **neutrinos now at the center of the stage**

neutrinos may shed light on the flavor and strong CP problem

dark matter can mediate neutrino mass generation

bright future for oscillation studies

unitarity tests necessary for the robustness of the CP programme

neutrinoless double-beta decay may determine Majorana phase

colliders have a great neutrino physics potential !

thanks!