neutrino pathways to new physics

José W F Valle

IFIC

ASTROPARTICLES
Astroparticles and High Energy Physics Group

CSIC
Consejo Superior de Investigaciones Científicas

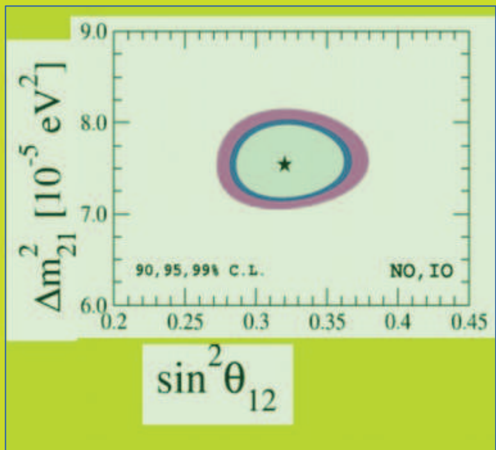
Vniversitat de València

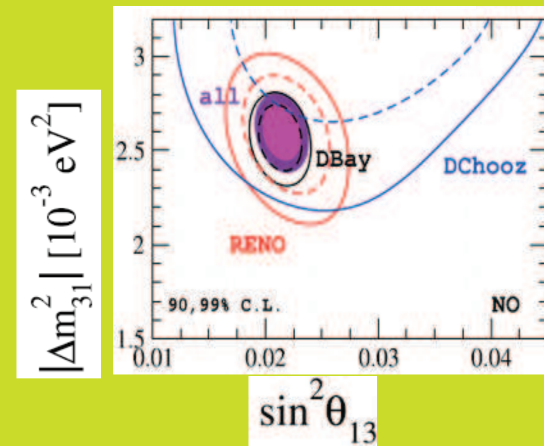
Excelencia Severo Ochoa

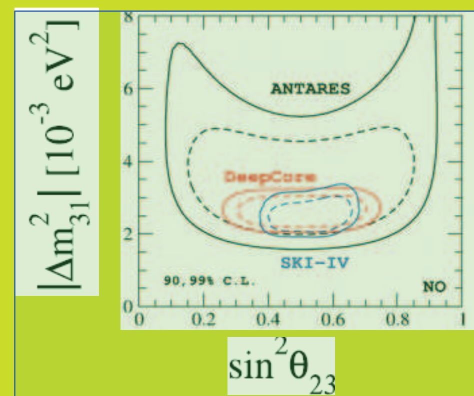
PASCOS 2019

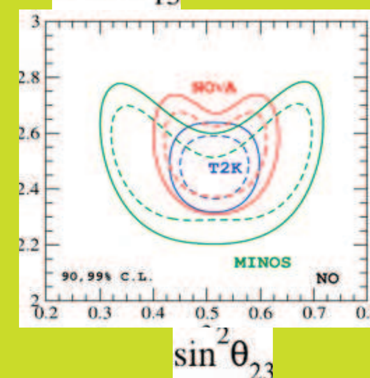
Manchester (July 2019)

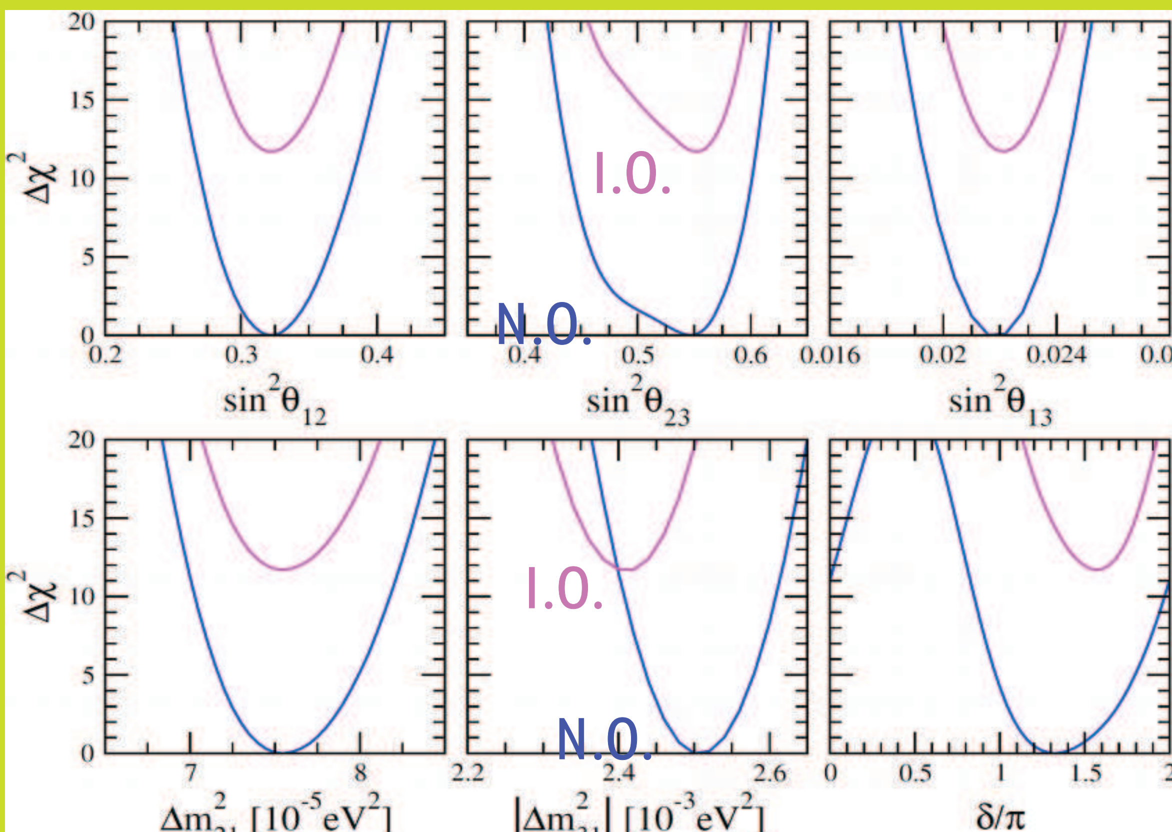
status of neutrino oscillations











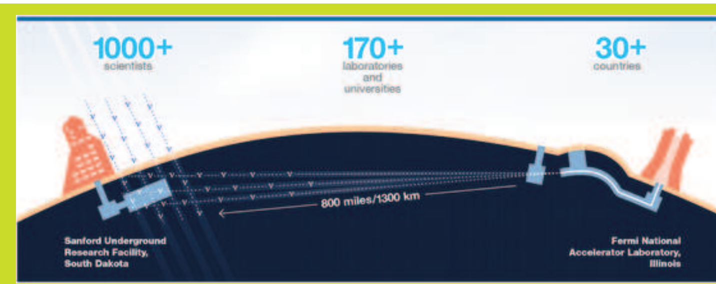
P.F. de Salas et al, PLB782 (2018) 633
https://globalfit.astroparticles.es/

Consistent global picture
Good agreement amongst groups

mass ordering : normal @ >3σ

- CP phase
- atm octant

leptonic CP violation

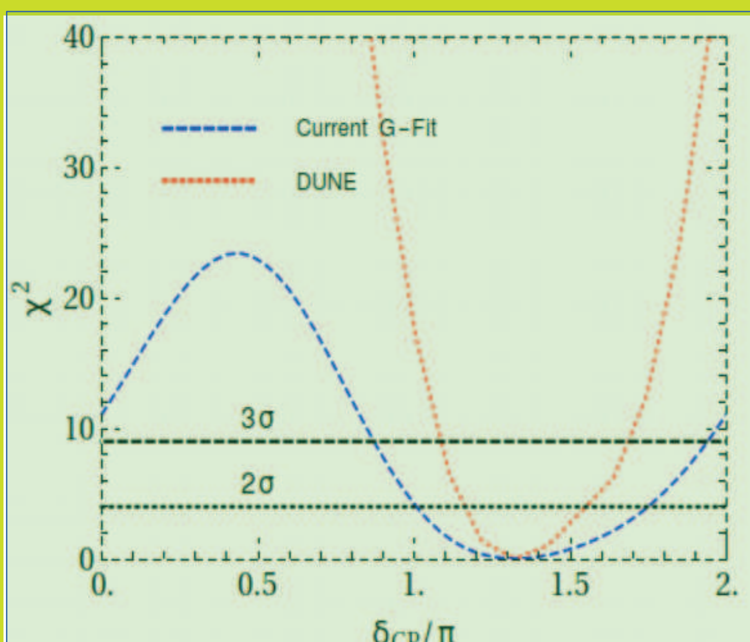


P.F. de Salas et al, PLB782 (2018) 633
https://globalfit.astroparticles.es/

improve at the next generation experiments

CP phase

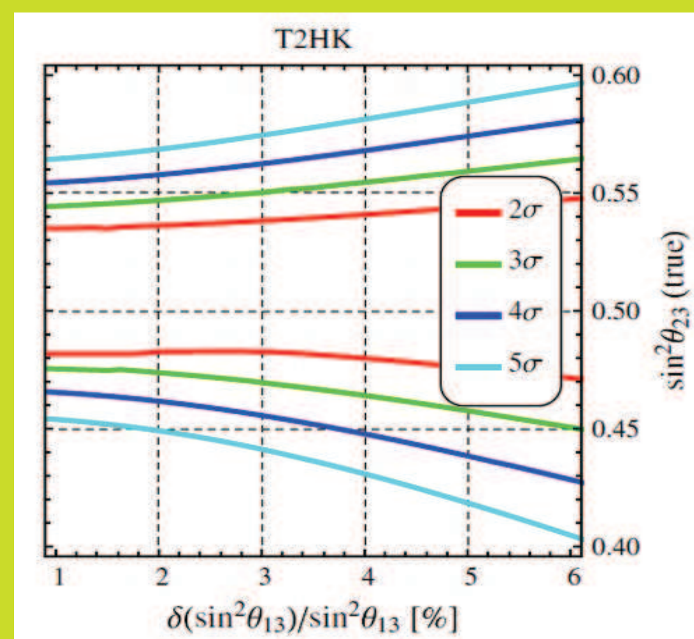
from
1811.07040



atm octant

from
Phys. Rev. D 96, 011303(R)

See also, e.g.
Phys.Rev. D97 (2018) 095025



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

TBM lepton mixing pattern

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

CP ⇒

$$\begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{e^{-i\rho}\cos\theta}{\sqrt{3}} & -\frac{ie^{-i\rho}\sin\theta}{\sqrt{3}} \\ -\frac{e^{i\rho}}{\sqrt{6}} & \frac{\cos\theta}{\sqrt{3}} - \frac{ie^{-i\sigma}\sin\theta}{\sqrt{2}} & \frac{e^{-i\sigma}\cos\theta}{\sqrt{2}} - \frac{i\sin\theta}{\sqrt{3}} \\ \frac{e^{i(\rho+\sigma)}}{\sqrt{6}} & -\frac{e^{i\sigma}\cos\theta}{\sqrt{3}} - \frac{i\sin\theta}{\sqrt{2}} & \frac{\cos\theta}{\sqrt{2}} + \frac{ie^{i\sigma}\sin\theta}{\sqrt{3}} \end{bmatrix}$$

⇒

$$\sin^2\theta_{12} = \frac{\cos^2\theta}{\cos^2\theta + 2}, \qquad \sin^2\theta_{23} = \frac{1}{2} + \frac{\sqrt{6}\sin 2\theta \sin\sigma}{2\cos^2\theta + 4}$$

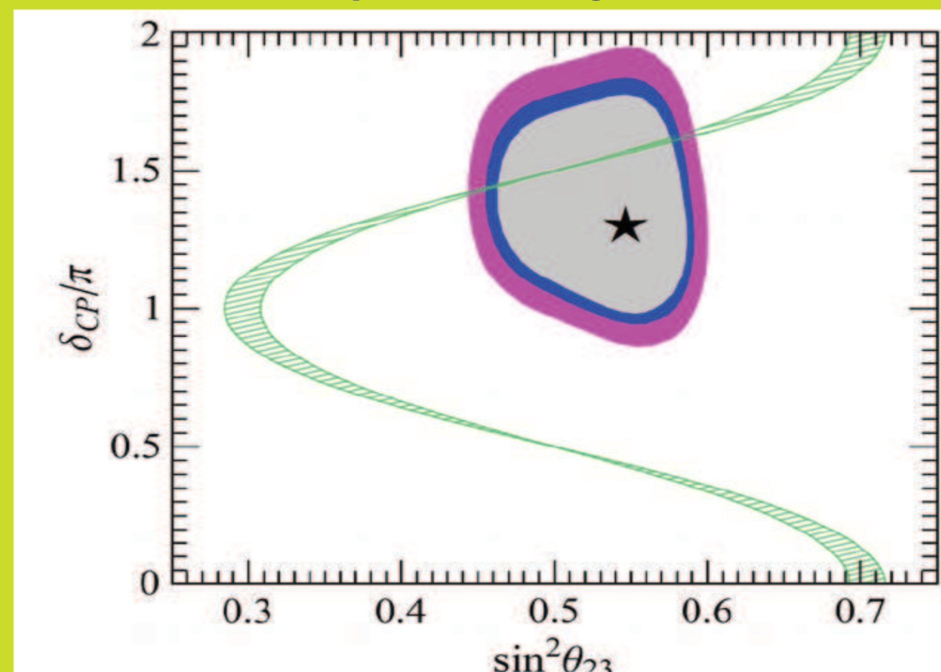
$$\sin^2\theta_{13} = \frac{\sin^2\theta}{3}, \qquad \tan\delta_{CP} = \frac{(\cos^2\theta + 2)\cot\sigma}{5\cos^2\theta - 2},$$

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

systematic CP revamp

predicting solar

predicting CP



from Phys.Rev. D98 (2018) 055019

Harrison, Scott & Perkins 2002
P 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

Several other
Revamped TBM ansatze
possible

Bi-Large lepton mixing pattern

from 1904.05632

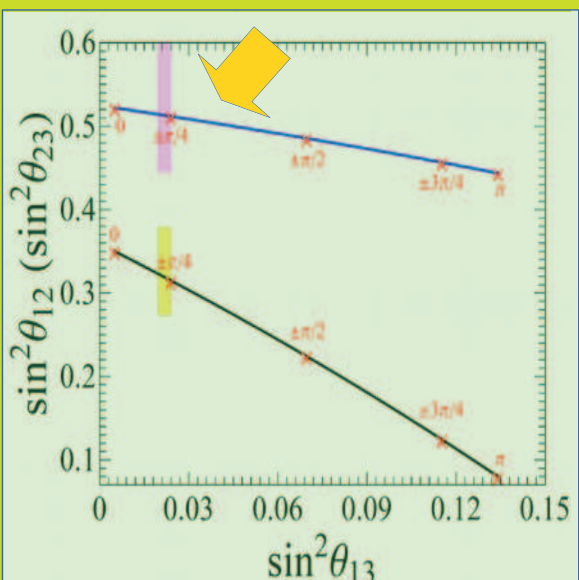
$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & -\lambda e^{i\phi} & A\lambda^3 e^{i\phi} \\ \lambda e^{-i\phi} & 1-\frac{1}{2}\lambda^2 & -A\lambda^2 \\ 0 & A\lambda^2 & 1 \end{bmatrix} \quad \begin{bmatrix} 1-\frac{5\lambda^2}{2} & 2\lambda & -\lambda \\ -2\lambda+3\lambda^2 & 1-\frac{13\lambda^2}{2} &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

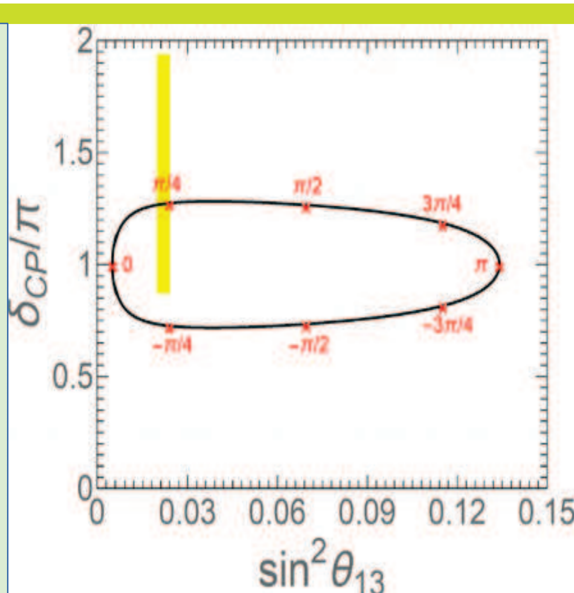
Largest Q similar to smallest L -mixing

Cabibbo angle as universal seed for flavor mixing

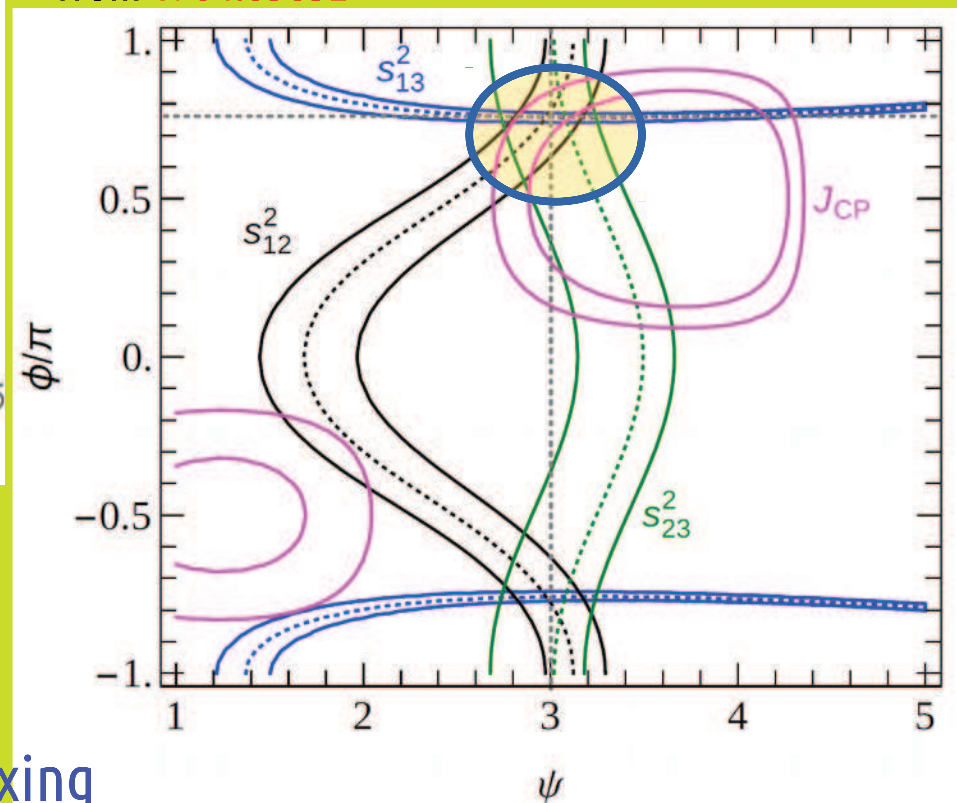
Phys.Rev. D86 (2012) 051301
Phys.Rev.D87 (2013) 053013
Phys.Lett. B748 (2015) 1-4
Phys.Lett. B792 (2019) 461-464

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





from 1904.05632



predicting solar, atm & CP from reactor angle

also 2-parameter generalizations of Bi-Large mixing

robustness

J.V. Phys.Lett. B199 (1987) 432-436
Miranda & J.V. Nucl.Phys. B908 (2016) 436
Escrihuela et al, Phys.Rev. D92 (2015) 053009

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

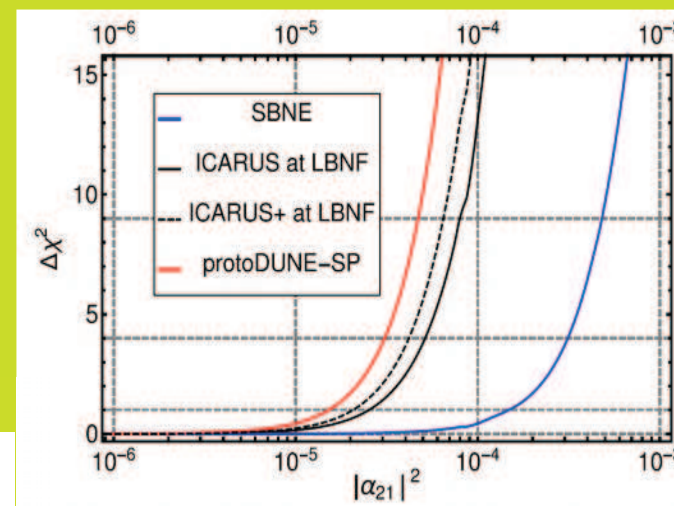
unitarity test as seesaw scale probe

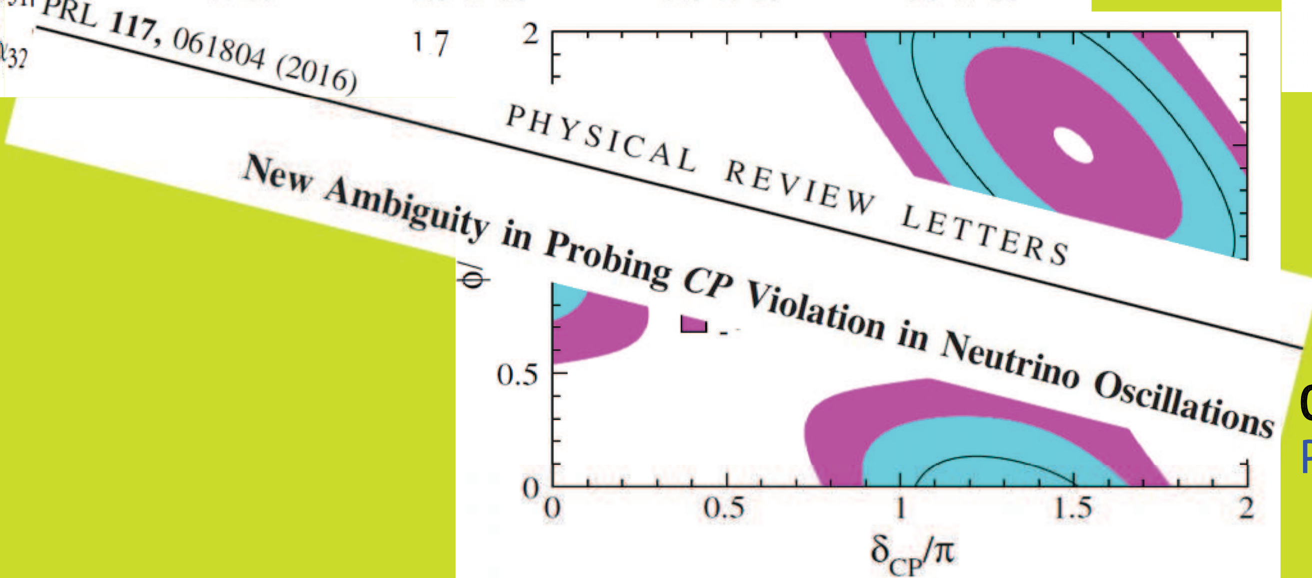
Phys.Rev. D95 (2017) 033005
New J. Phys. 19 (2017) 093005

	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
$\|\alpha_{21}\|<$	1.0×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	3.6×10^{-2}
$\|\alpha_{31}\|<$	4.2×10^{-2}	9.8×10^{-2}	9.0×10^{-2}	1.3×10^{-1}
$\|\alpha_{32}\|<$		1.7		

window to BSM physics

PRD97 (2018) 095026

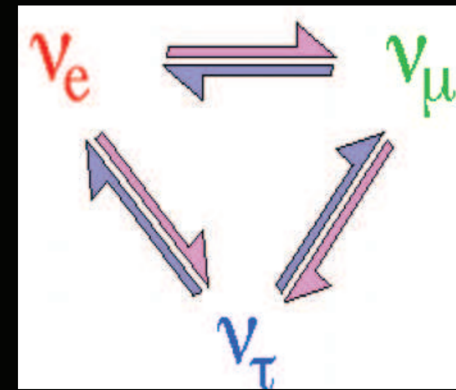




nsi Coloma, Huber et al, Miranda et al, de Gouvea et al, Goswami et al, Kopp et el, Antusch et al, Fernandez, Lopez Pavon, et al ...

CP ambiguity Miranda et al, Phys.Rev.Lett. 117 (2016) 061804

new Physics at last!!



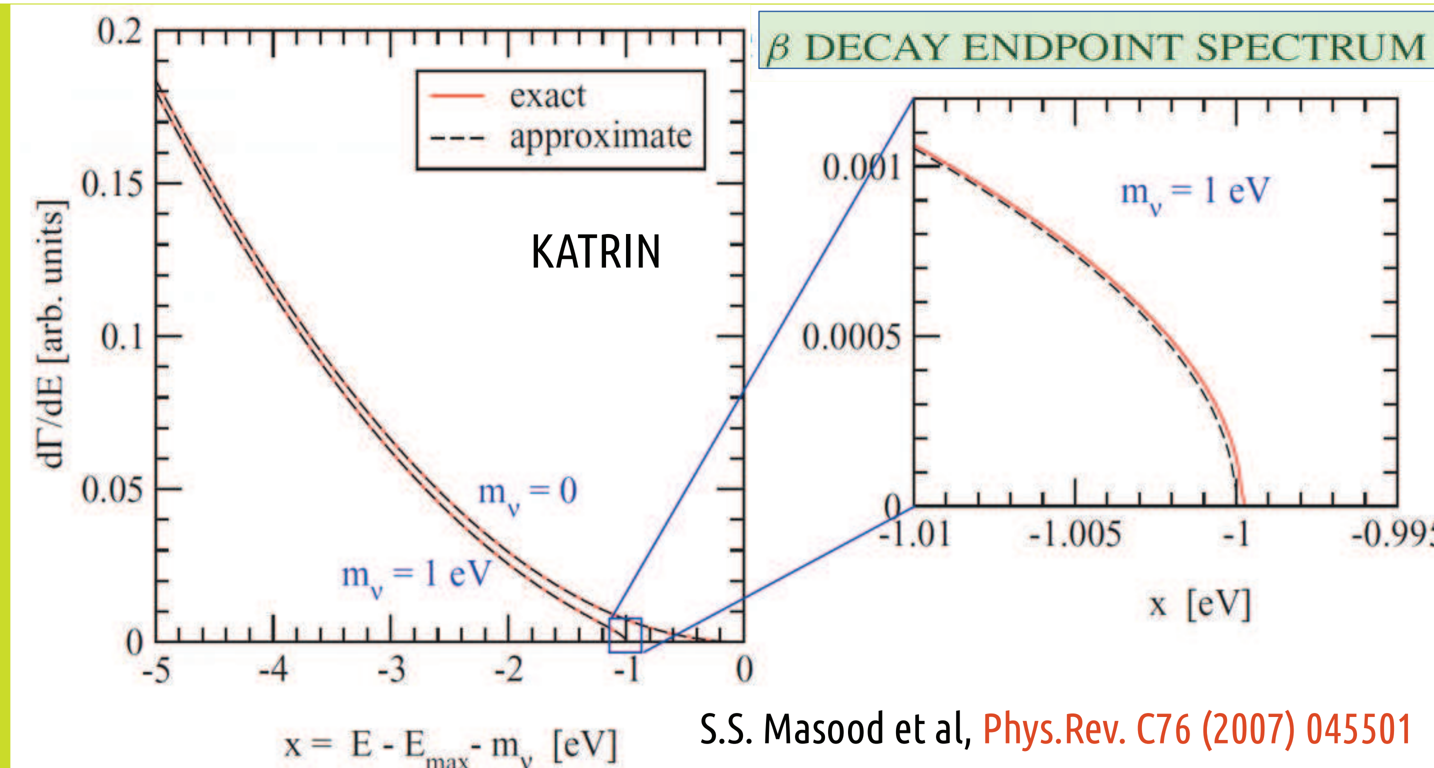
Oscillations bring neutrinos to the center of particle physics

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

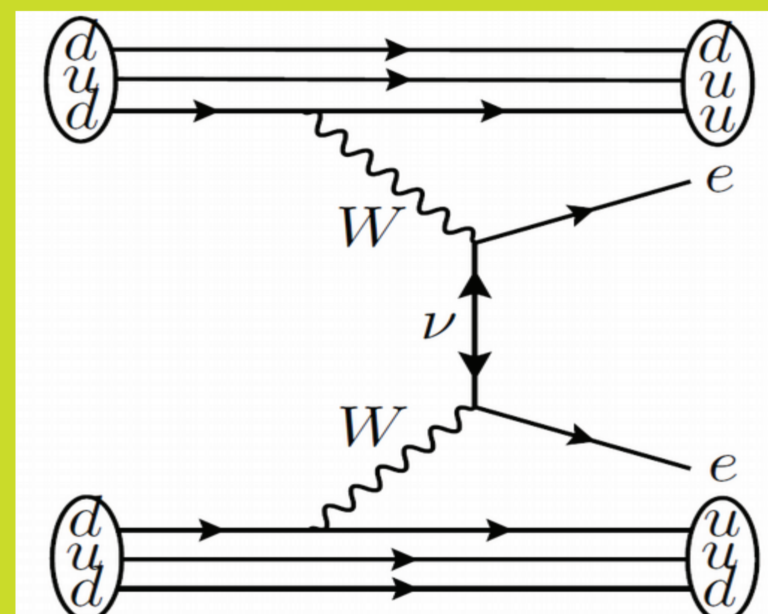
besides neutrino mass there are other issues in particle physics & cosmology for which neutrinos may provide key input

the portals : flavor, EW breaking, unification, DM …

nuclear physics as probe of neutrino mass scale



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



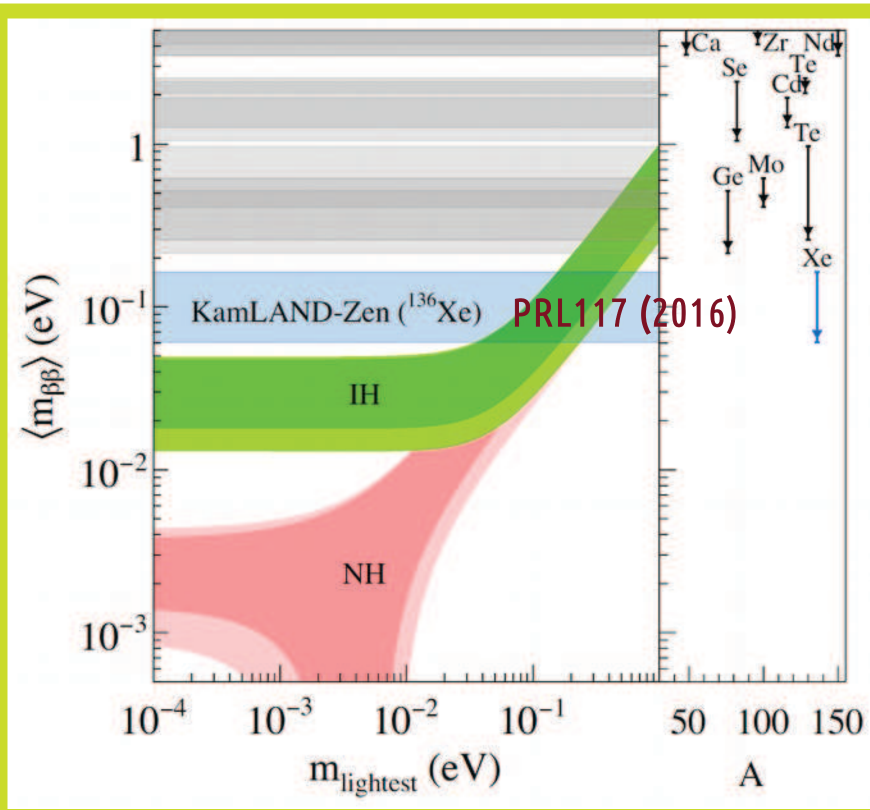
neutrinoless doublebeta decay

symmetric parametrization of lepton mixing matrix

Schechter & JV PRD22 (1980) 2227

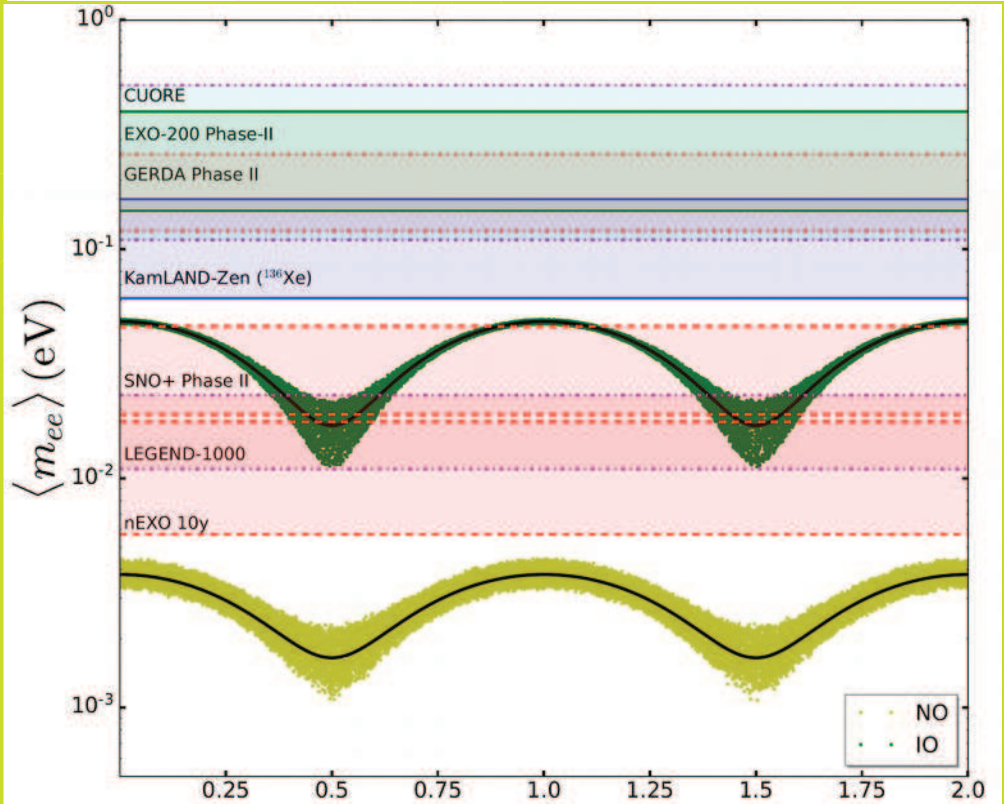
Rodejohann, JV Phys.Rev. D84 (2011) 073011

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



PRL117 (2016)

nEXO, CUORE , LEGEND (nGERDA/Majorana) ...

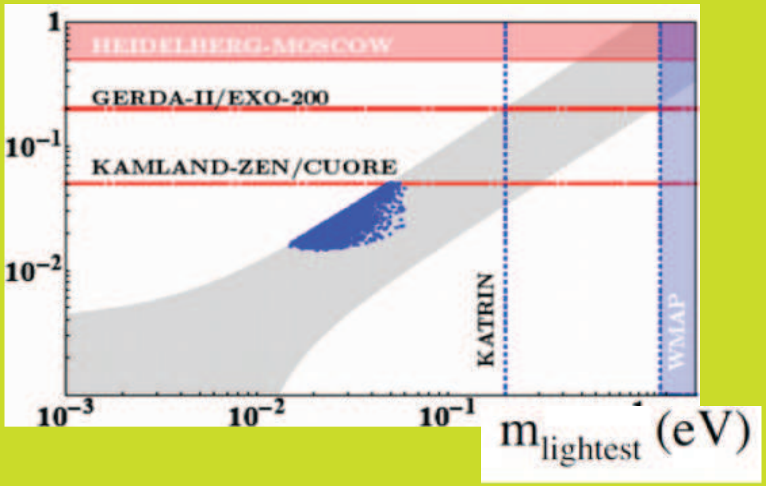


Majorana phase

if one neutrino is massless

From Phys.Lett. B790 (2019) 303-307

neutrinoless doublebeta decay



flavor sensitivity

lower bounds even for normal ordering

Dorame et al
NPB861 (2012) 259-270

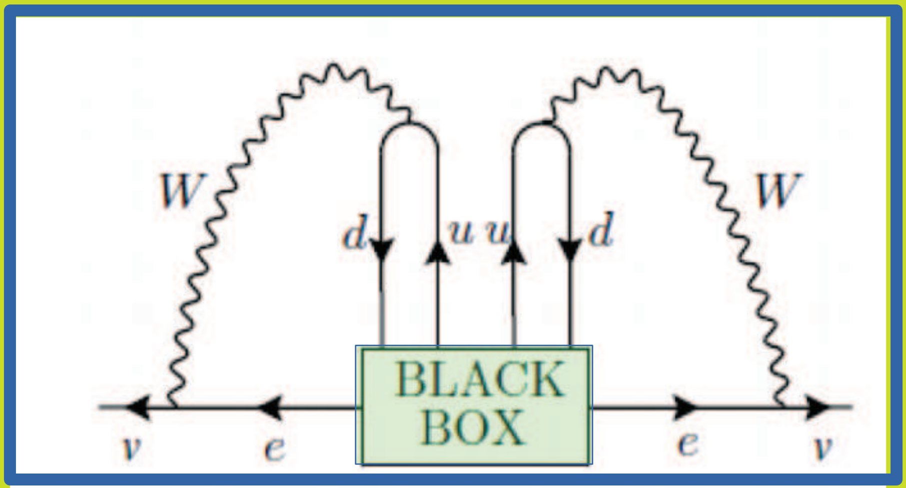
Dorame et al
PhysRevD.86.056001

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

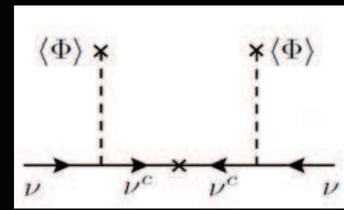
significance

Schechter, Valle 82

Lindner et al JHEP 1106 (2011) 091

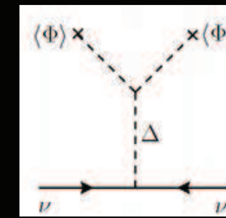


Origin of neutrino mass



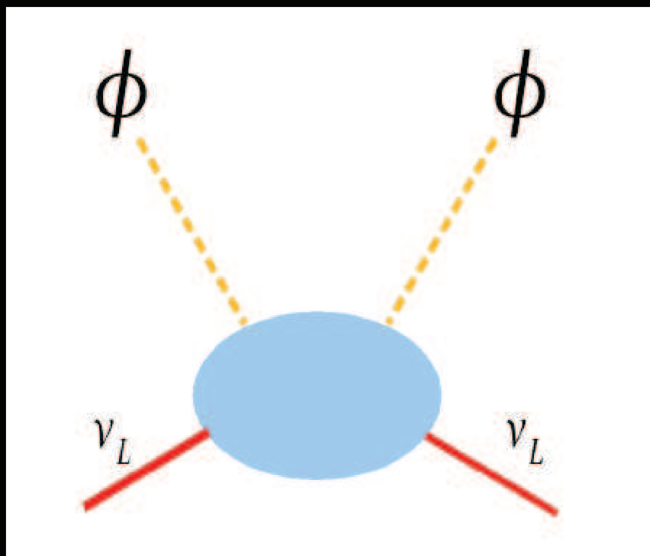
TYPE I

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

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

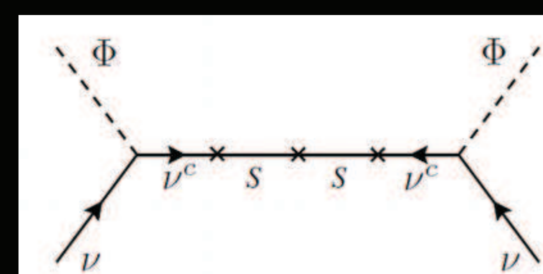
coefficient
mechanism
scale
flavor structure

any number of singlet R's w.r.t. L's

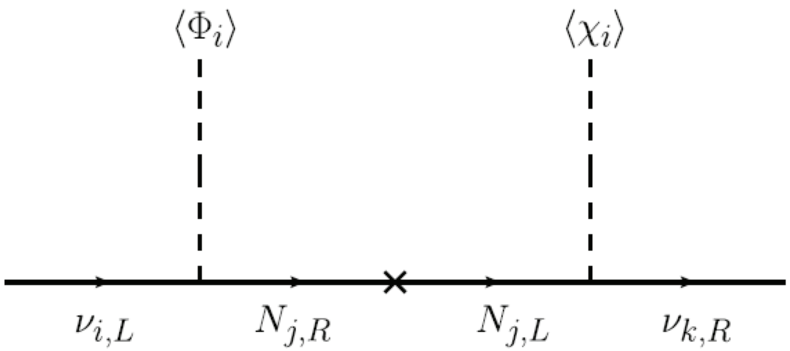
(3,2)SEESAW (3,1) SCOTO-SEESAW...

(3,6) LOW-SCALE SEESAW

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



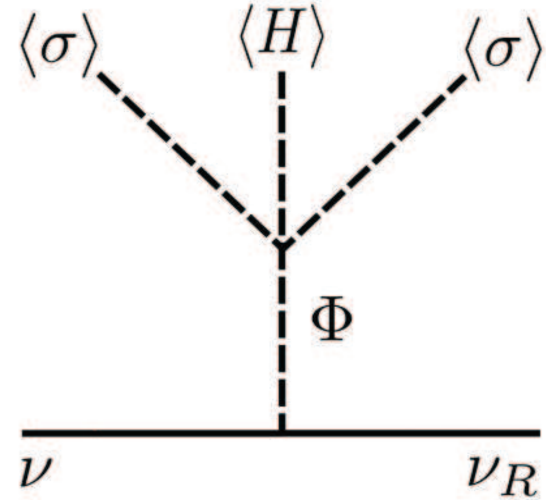
seesawing a la Dirac



type1

Phys.Lett. B761 (2016) 431-436

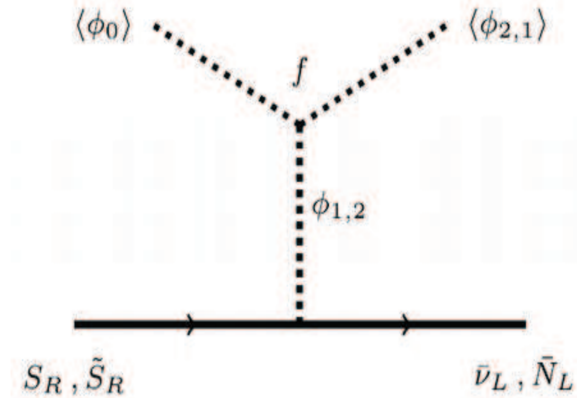
Phys.Lett. B767 (2017) 209-213



type2

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



symmetry protects small neutrino mass

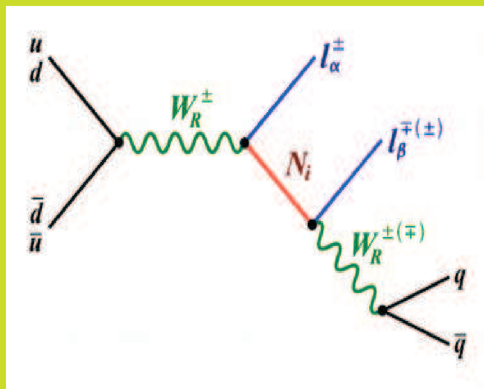
Phys.Rev. D98 (2018) 035009

Phys.Lett. B781 (2018) 122-128

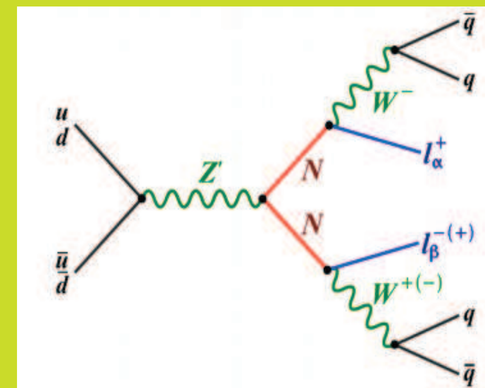
Addazi et al Phys.Lett. B759 (2016) 471-478

Phys.Lett. B755 (2016) 363-366

mediator searches with new gauge portal

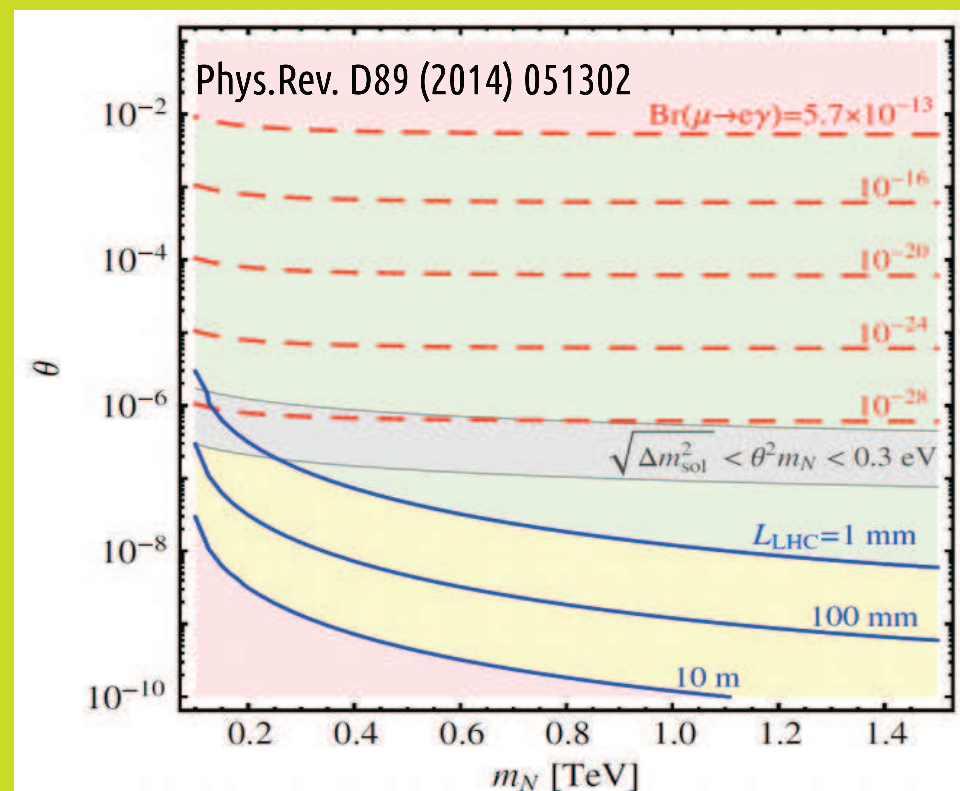


extended EW theory



charged lepton flavor violation as a HE phenomenon?

Phys.Rev. D86 (2012) 055006 &
Deppisch, Dev & Pilaftsis New J.Phys. 17 (2015) 075019



radiative neutrino mass in extended EW theory

331 motivation   # families = # colours

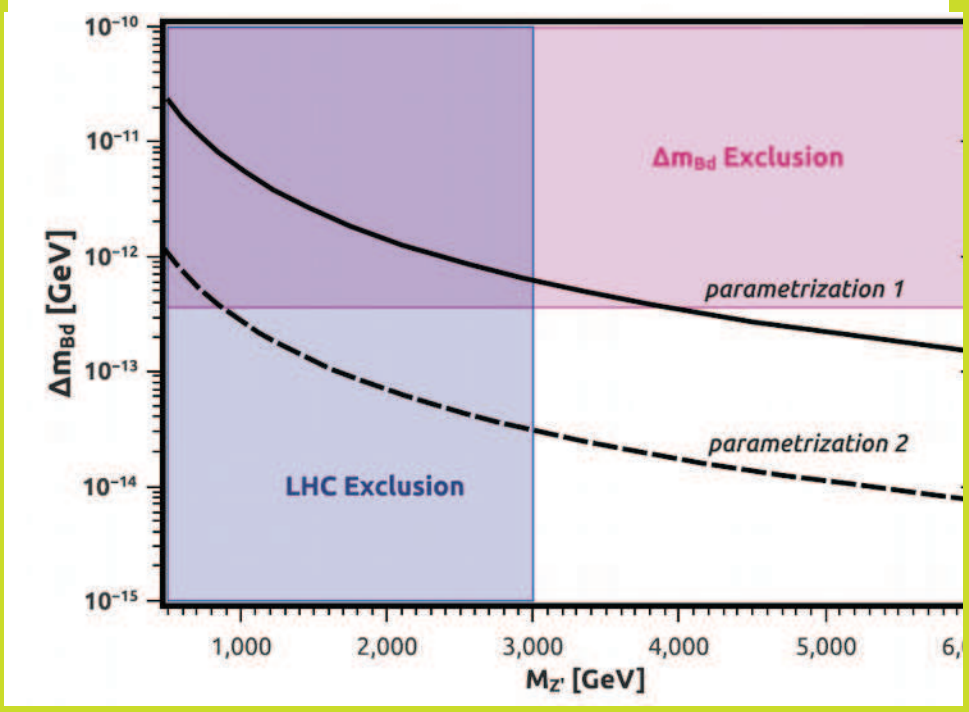
Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

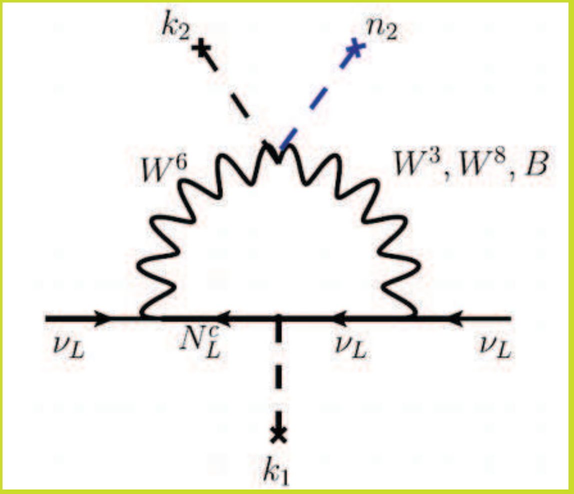
low scale

calculable neutrino mass

Gauge nu-mass mediators

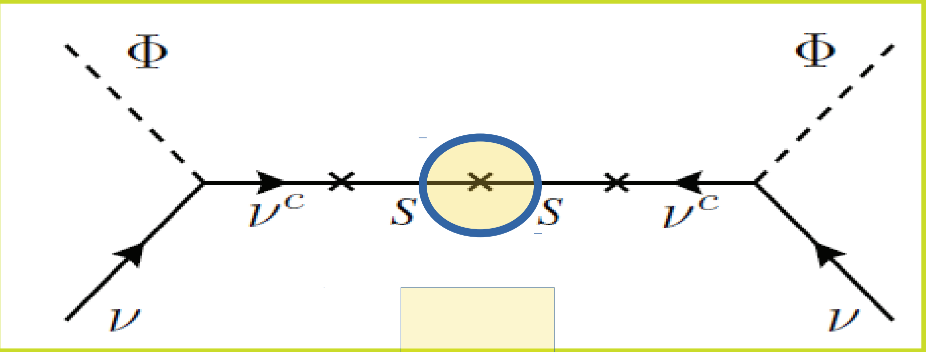
F.S. Queiroz et al. / Physics Letters B 763 (2016) 269–274

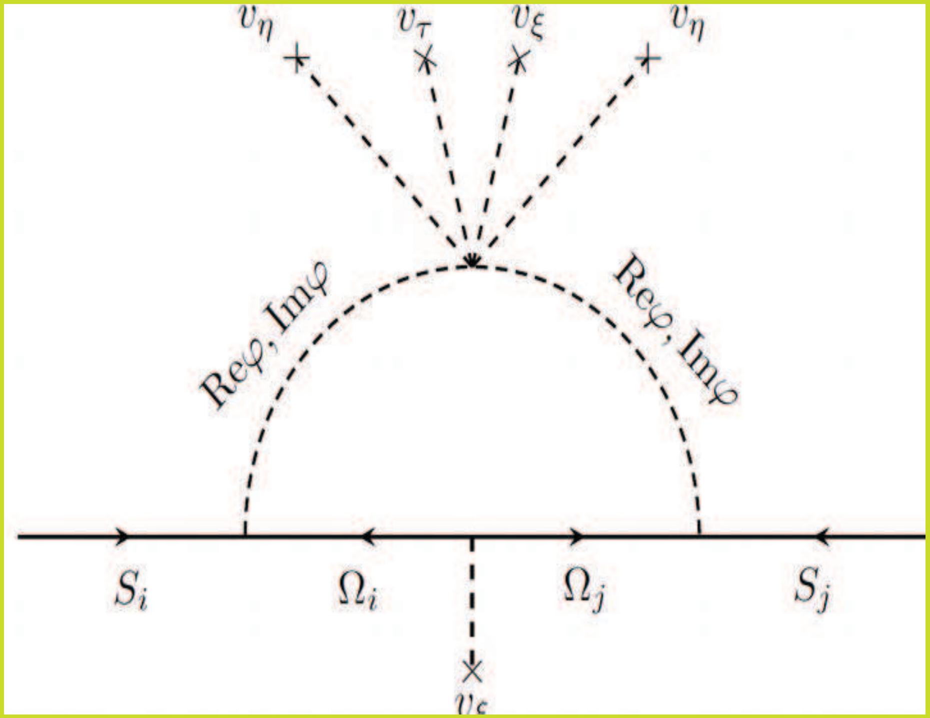




Boucenna, Morisi, JV Phys.Rev. D90 (2014) 013005

combining low scale seesaw with radiative corrections





radiative inverse/linear seesaw mechanism

See also
Phys.Rev. D81 (2010) 051701

Cárcamo Hernández et al JHEP 1902 (2019) 065

Flavors

SM lacks an organizing principle to understand flavor

Simplest flavor symmetry

A4

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

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

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

$$e_R \quad \mu_R \quad \tau_R$$

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

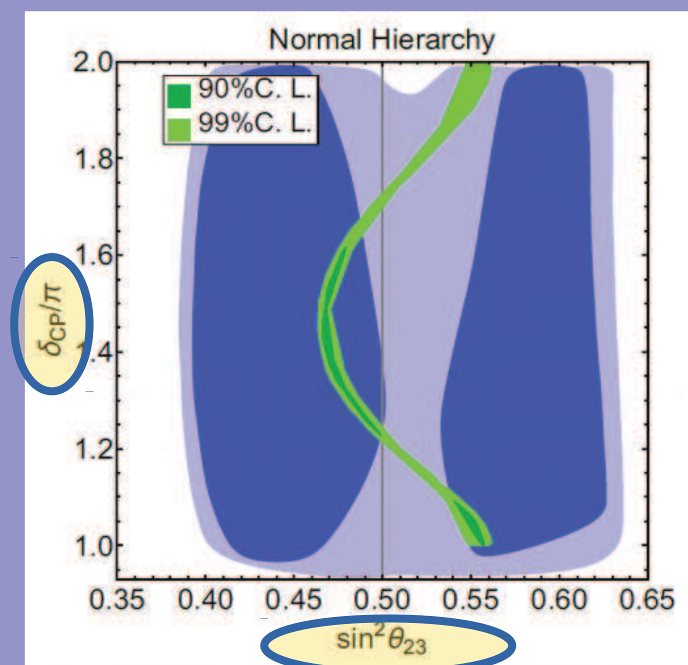
$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R$$

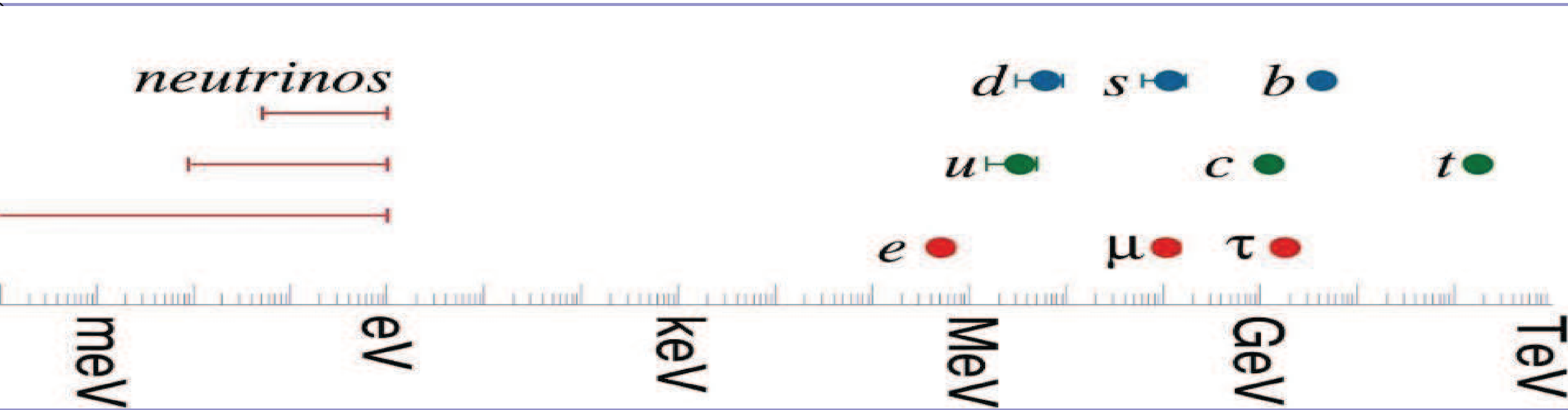
Babu-Ma-Valle PLB552 (2003) 207
Hirsch et al PRD69 (2004) 093006

still good starting points ... predictive
revamping ... Morisi et al, Phys.Rev. D88 (2013) 016003

Constrained global fit
Phys.Lett. B774 (2017) 179-182



to be probed at LBL experiments, e.g. DUNE...



from oscillations to charged fermion masses

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 unification

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

flavor predictions from warped SM

constrained global fitting

Chen et al JHEP01(2016)007

mass hierarchies from geometry

⇒ angles related by symmetry

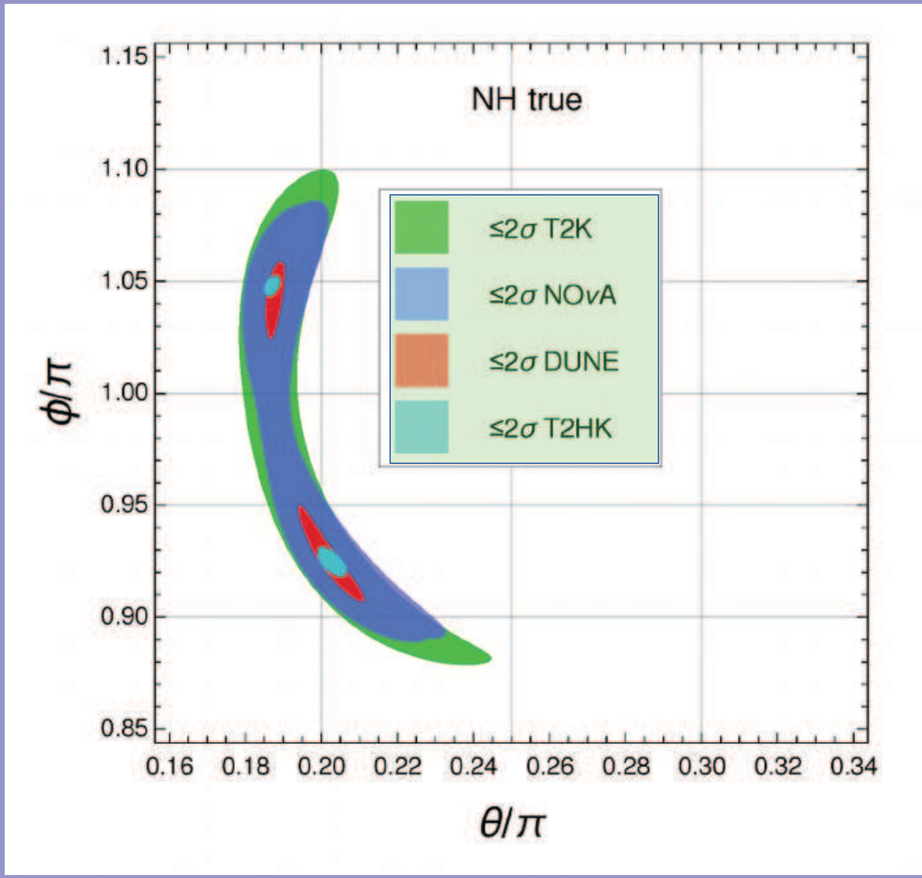
$$\sin^2\theta_{12} = \frac{1}{2-\sin 2\theta_\nu \cos\phi_\nu}$$

$$\sin^2\theta_{13} = \frac{1}{3}(1+\sin 2\theta_\nu \cos\phi_\nu)$$

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

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

⇒



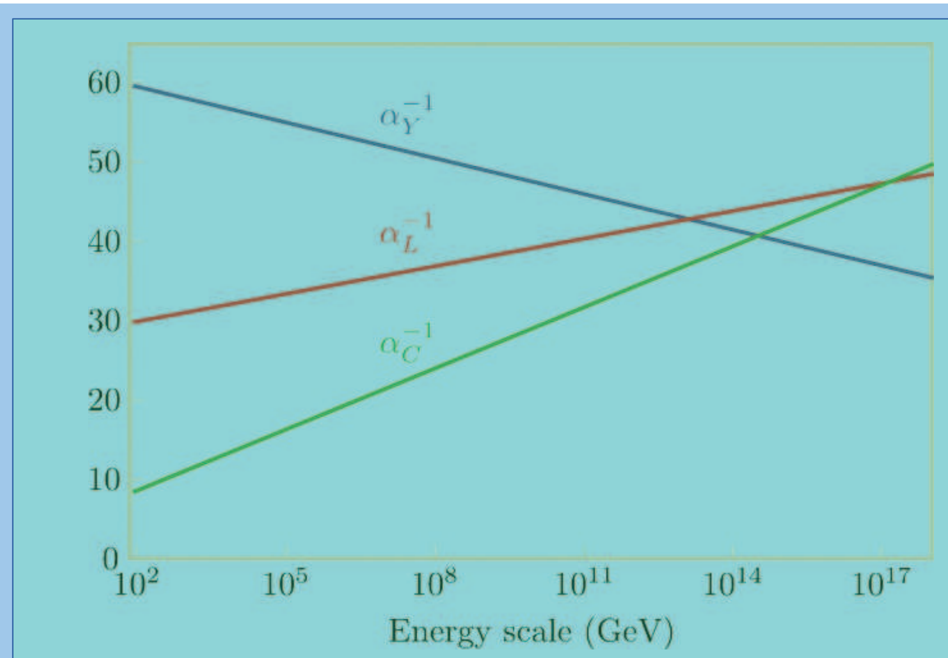
Predictions for LBL experiments

Phys. Rev. D95 (2017) 095030

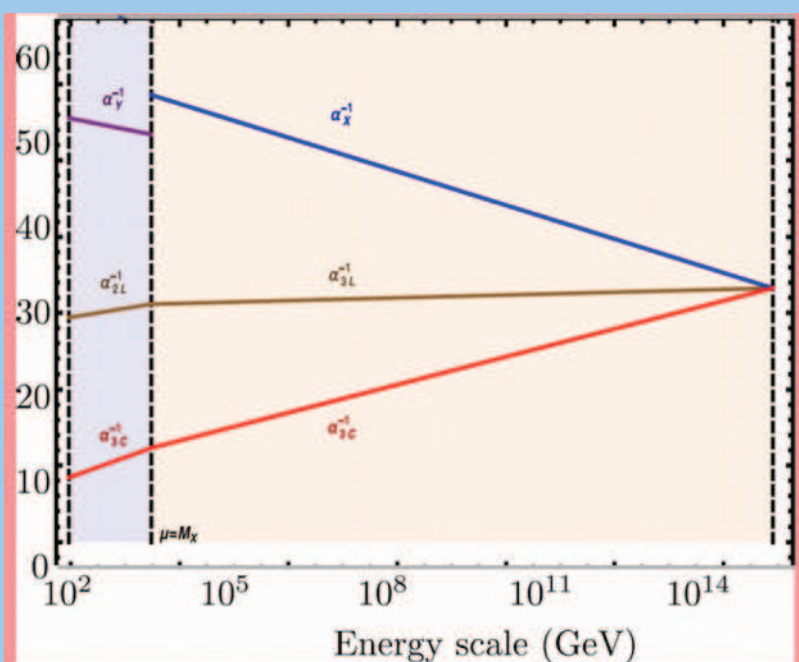
Phys.Lett. B771 (2017) 524

Standard model

although unification is missed ...
the ternd is there ...



SUSY would make the gauge couplings unify at GUT scale,
But ... so far no p decay nor super-partners ...



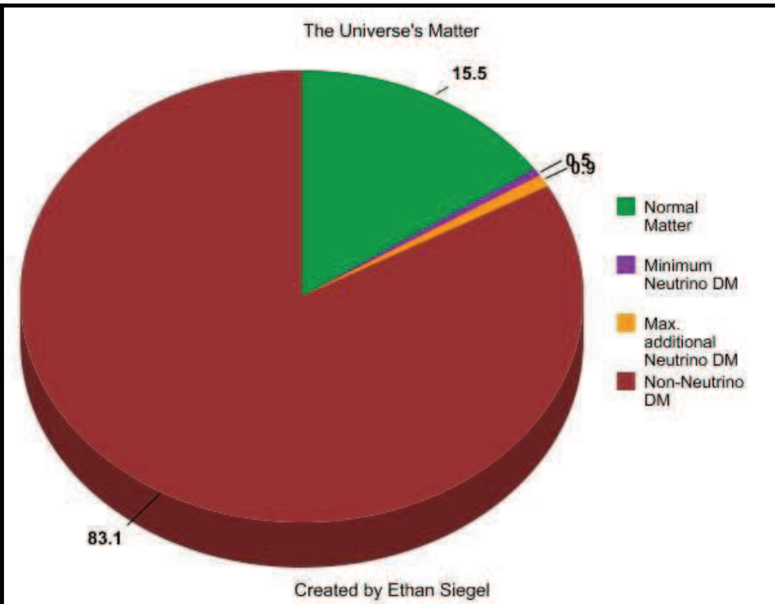
neutrinos & unification

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

E(6) F-theory GUT

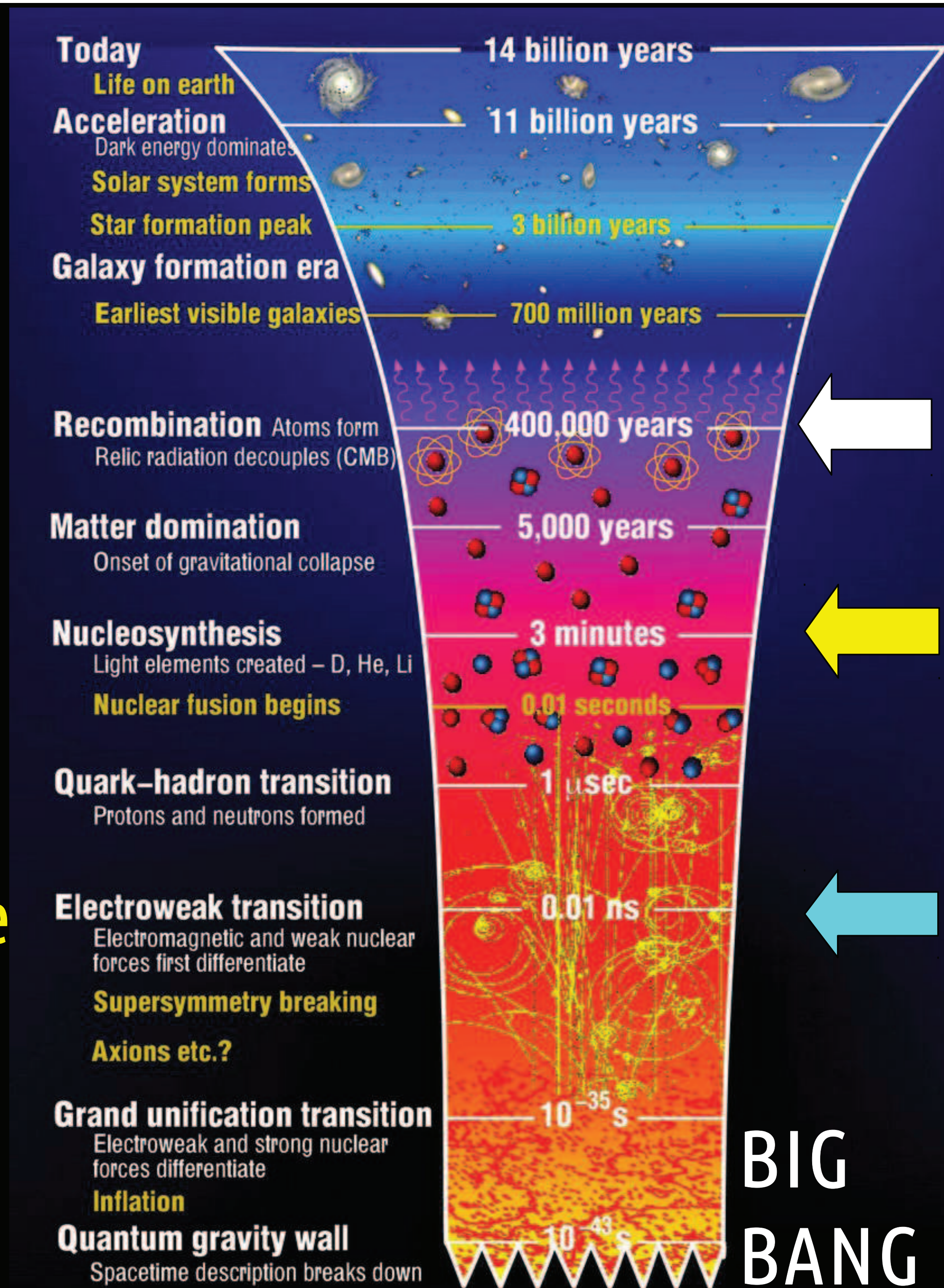
Boucenna et al Phys. Rev. D 91, 031702 (2015)

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



need for dark matter

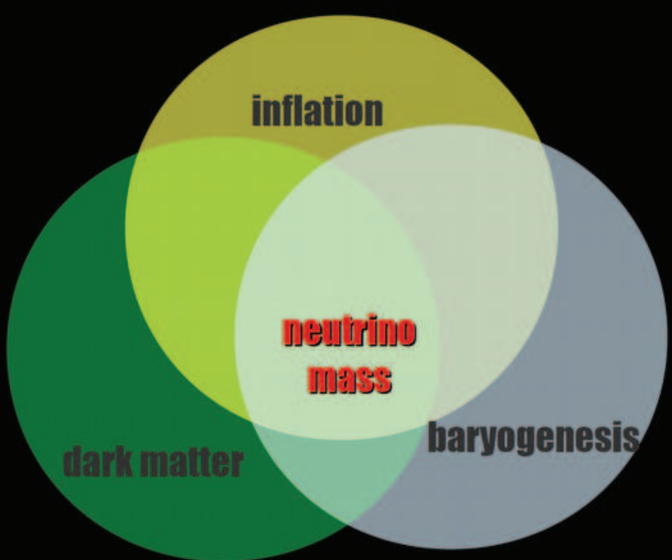
nu's at most 1% but can be key to understanding DM

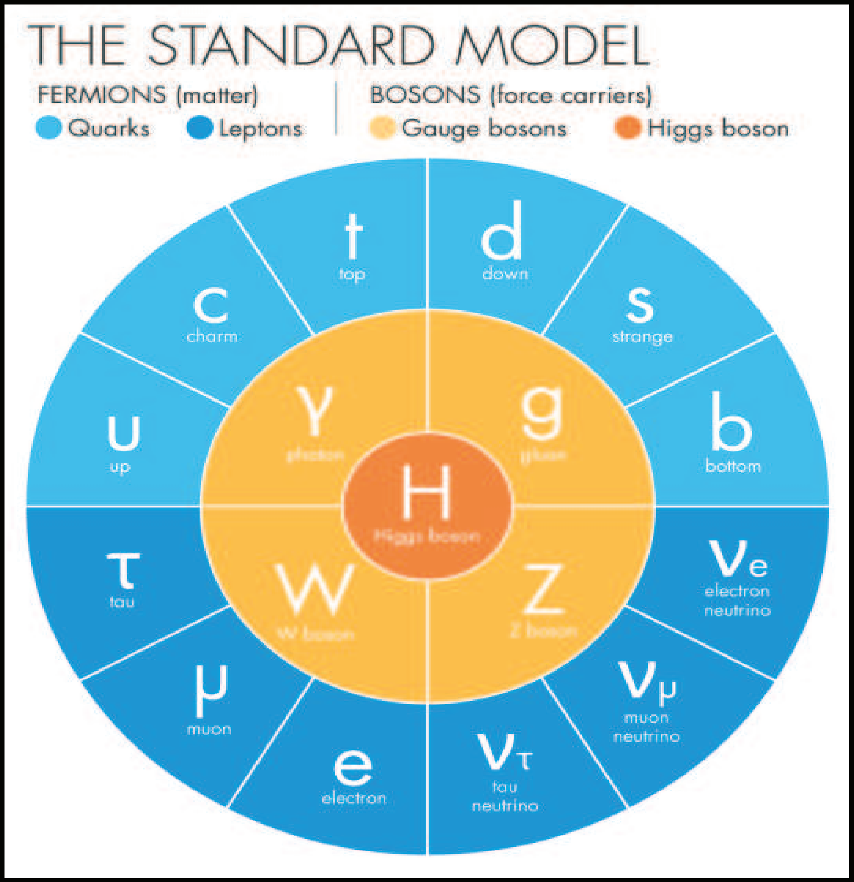


take home

- bright future for oscillation physics + nsi/non-unitarity
- searching mediators via LFV @ HE colliders
- neutrinos may shed light on flavor & unification
- comprehensive unification: forces & families
- neutrinos and EWSB

neutrino mass generation may be key to DM and other cosmological puzzles





THE END