

neutrinos and the challenges of particle physics

José W F Valle

IFIC

ASTROPARTICLES

Astroparticles and High Energy Physics Group

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



Neutrino Oscillation Workshop

Ostuni, September 9-16, 2018

exciting ...



Higgs not the last brick !

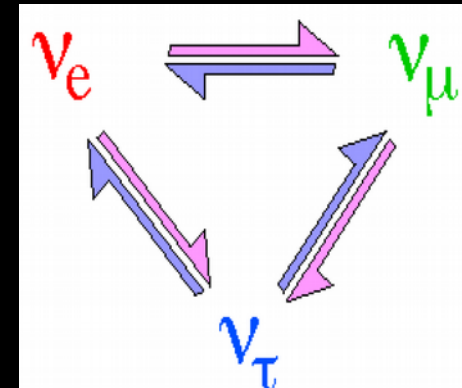
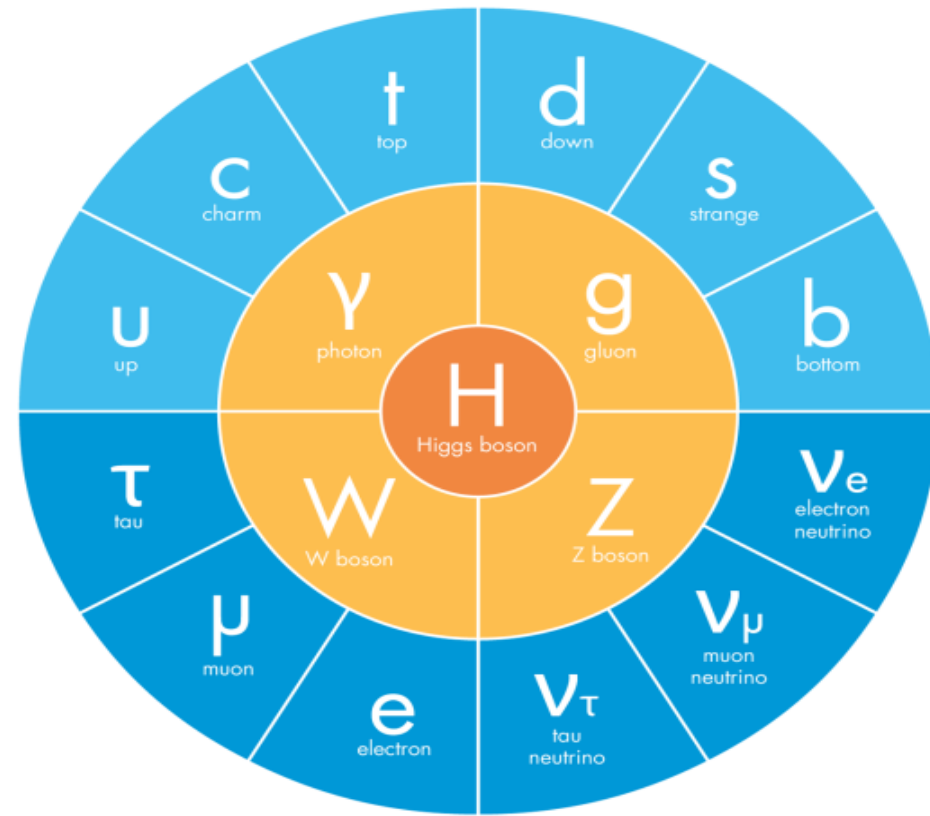
THE STANDARD MODEL

FERMIONS (matter)

● Quarks ● Leptons

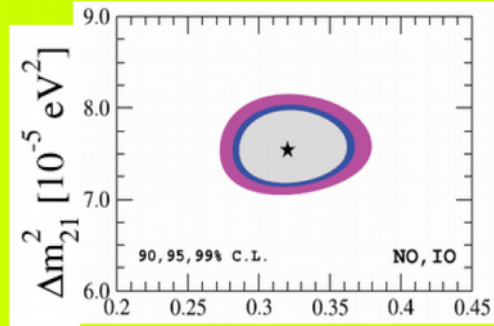
BOSONS (force carriers)

● Gauge bosons ● Higgs boson

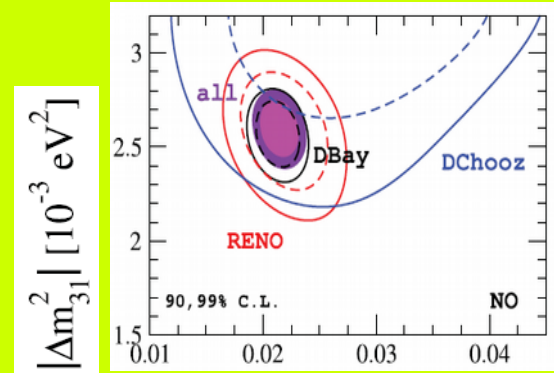


Besides neutrino mass there are many other issues in particle physics & cosmology for which neutrinos may provide key input

status of neutrino oscillations 2018

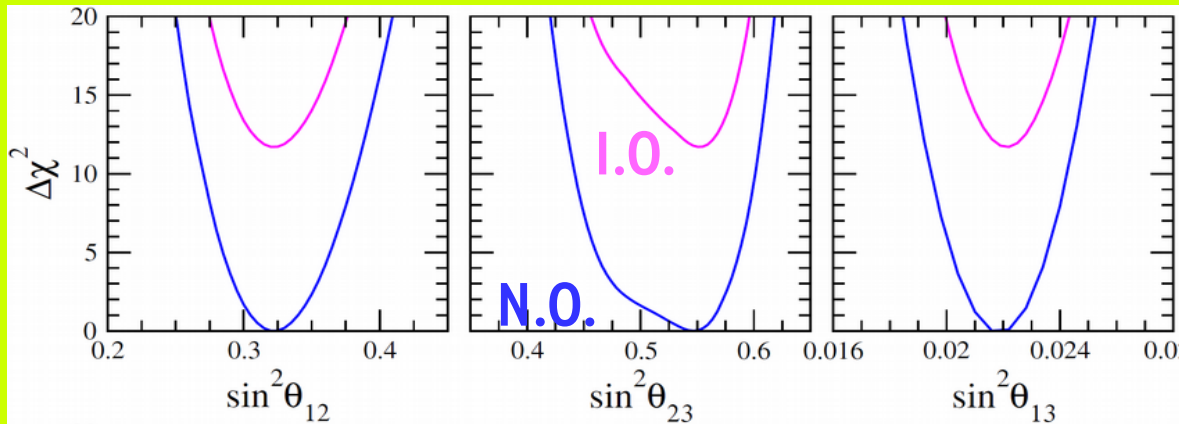


$\sin^2 \theta_{12}$

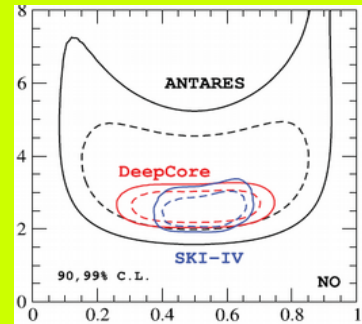


$|\Delta m_{31}^2| [10^{-3} \text{ eV}^2]$

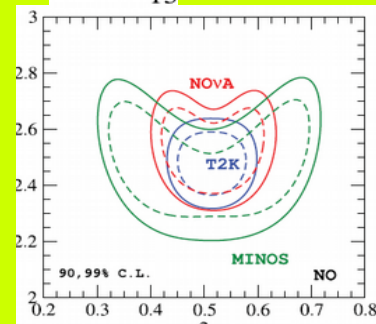
$\sin^2 \theta_{13}$



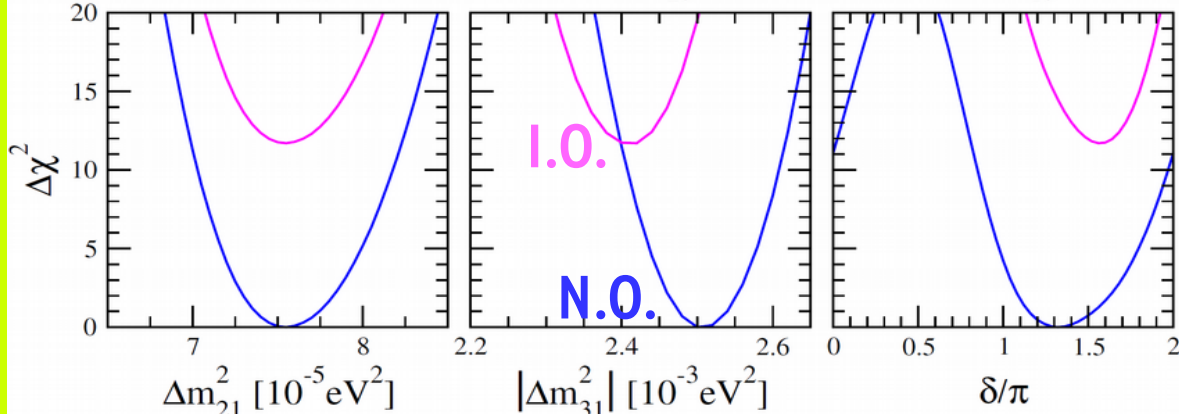
$|\Delta m_{31}^2| [10^{-3} \text{ eV}^2]$



$\sin^2 \theta_{23}$



$\sin^2 \theta_{23}$



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

Consistent global picture
Good agreement
Good long-term prospects

status of neutrino oscillations 2018

the numbers

Neutrino oscillation parameters summary determined from this global analysis. The ranges for inverted ordering refer to the local minimum for this neutrino mass ordering.

Parameter	Best fit $\pm 1\sigma$	2σ range	3σ range
Δm_{21}^2 [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (NO)	2.50 ± 0.03	2.44–2.57	2.41–2.60
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.34–2.47	2.31–2.51
$\sin^2 \theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/^\circ$	$34.5^{+1.2}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2 \theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.67–5.83	4.45–5.99
$\theta_{23}/^\circ$	$47.7^{+1.2}_{-1.7}$	43.1–49.8	41.8–50.7
$\sin^2 \theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.91–5.84	4.53–5.98
$\theta_{23}/^\circ$	$47.9^{+1.0}_{-1.7}$	44.5–48.9	42.3–50.7
$\sin^2 \theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	2.03–2.34	1.96–2.41
$\theta_{13}/^\circ$	$8.45^{+0.16}_{-0.14}$	8.2–8.8	8.0–8.9
$\sin^2 \theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	2.07–2.36	1.99–2.44
$\theta_{13}/^\circ$	$8.53^{+0.14}_{-0.15}$	8.3–8.8	8.1–9.0
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	1.01–1.75	0.87–1.94
$\delta/^\circ$	238^{+38}_{-27}	182–315	157–349
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94
$\delta/^\circ$	281^{+23}_{-27}	229–328	202–349

precision era requires robustness tests

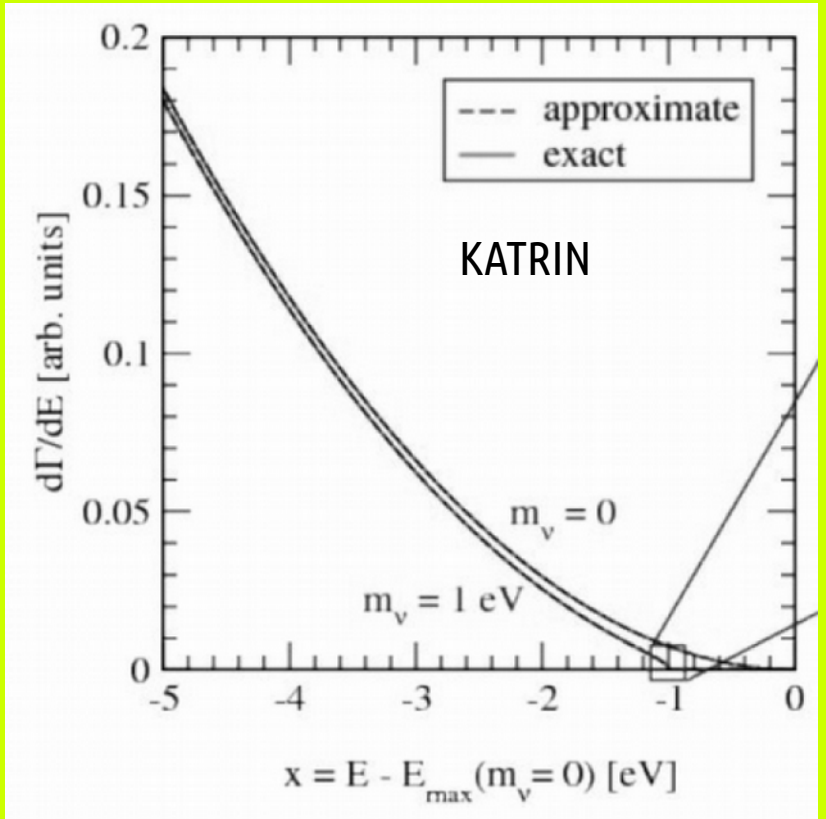
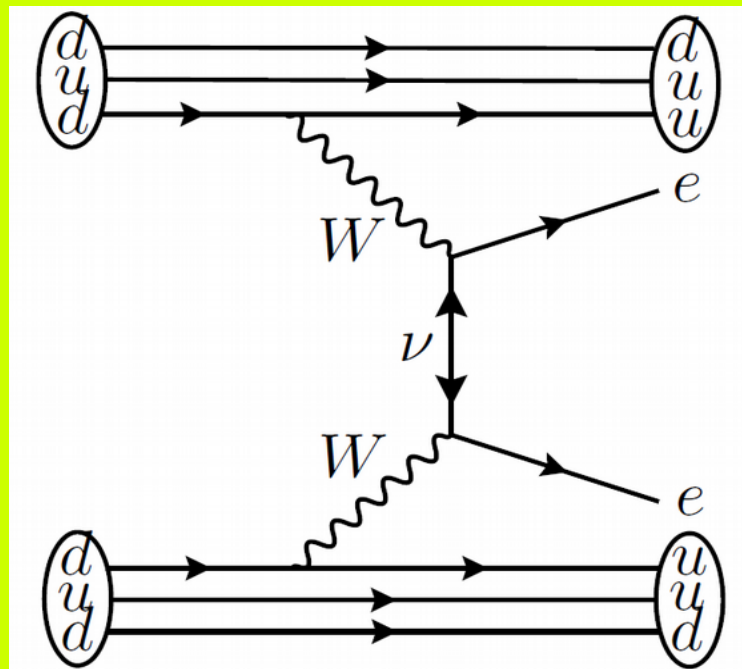
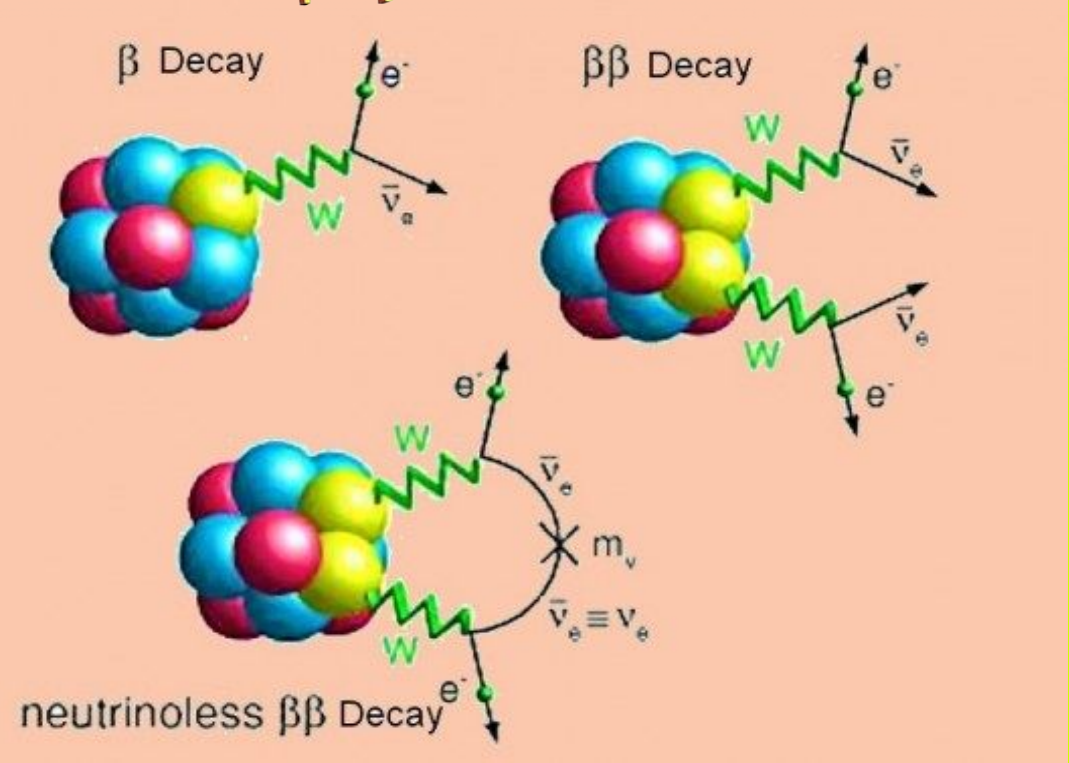
need to go beyond 3-nu paradigm

unitarity violation, nsi theory-motivated
light steriles, magnetic moments...

SN & cosmological implications

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

nuclear physics as probe of neutrino mass scale



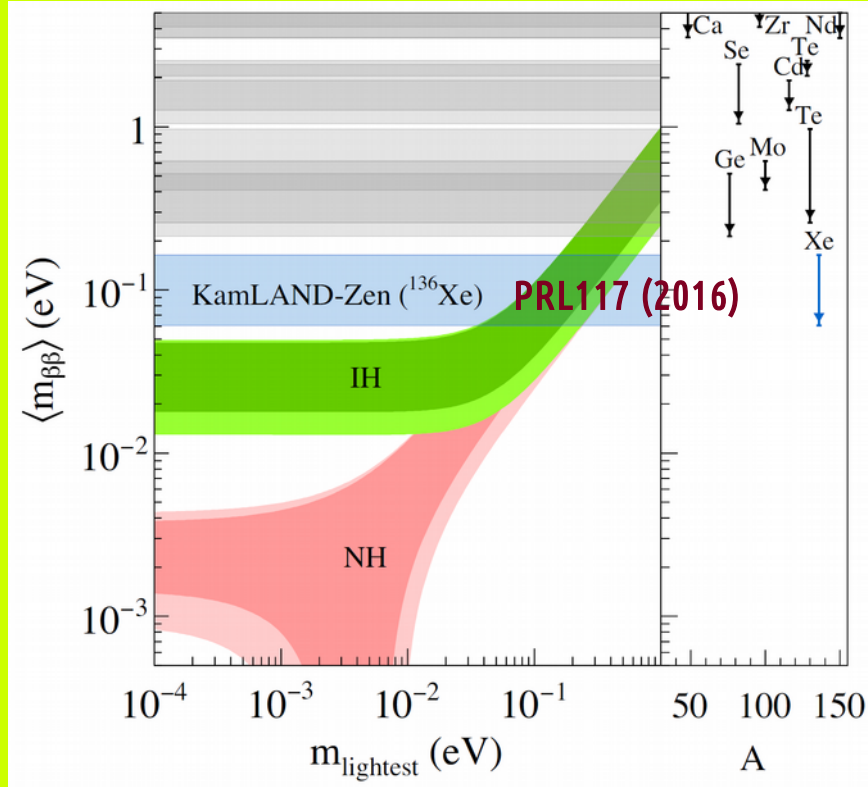
neutrinoless double beta decay

nice historical review
A.S. Barabash arXiv:1104.2714

old symmetric parametrization of lepton mixing matrix

Schechter & JV PRD22 (1980) 2227
Rodejohann, JV Phys.Rev. D84 (2011) 073011

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



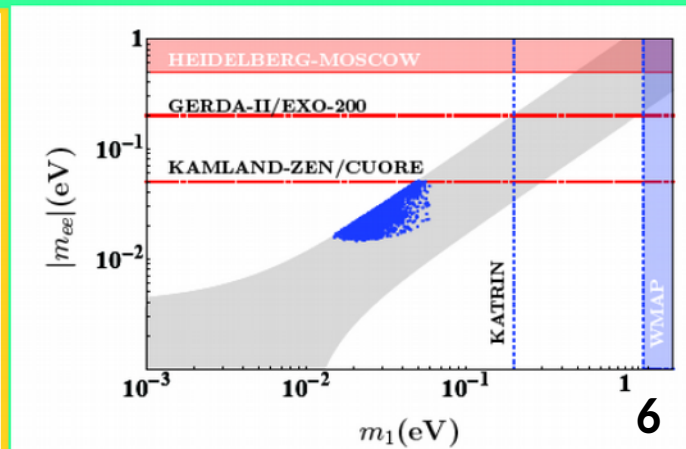
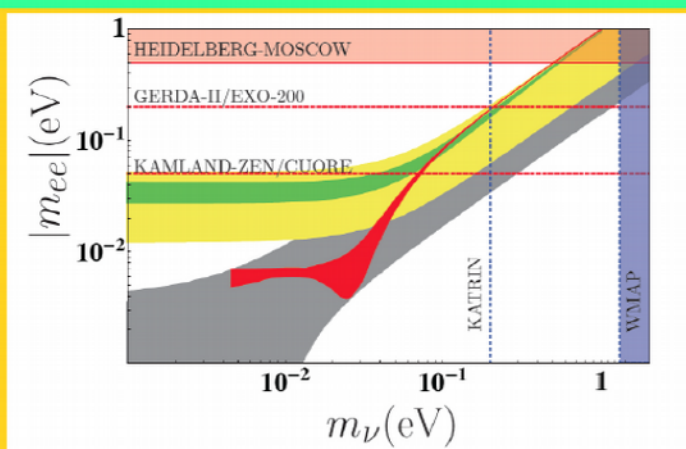
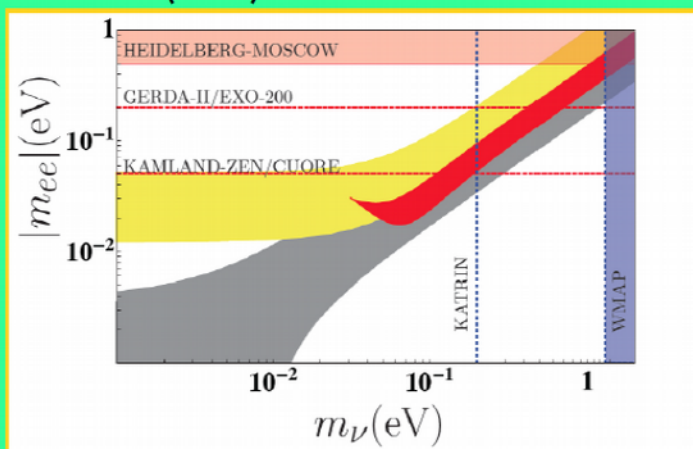
nEXO, CUORE, LEGEND (nGERDA/Majorana) ...

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

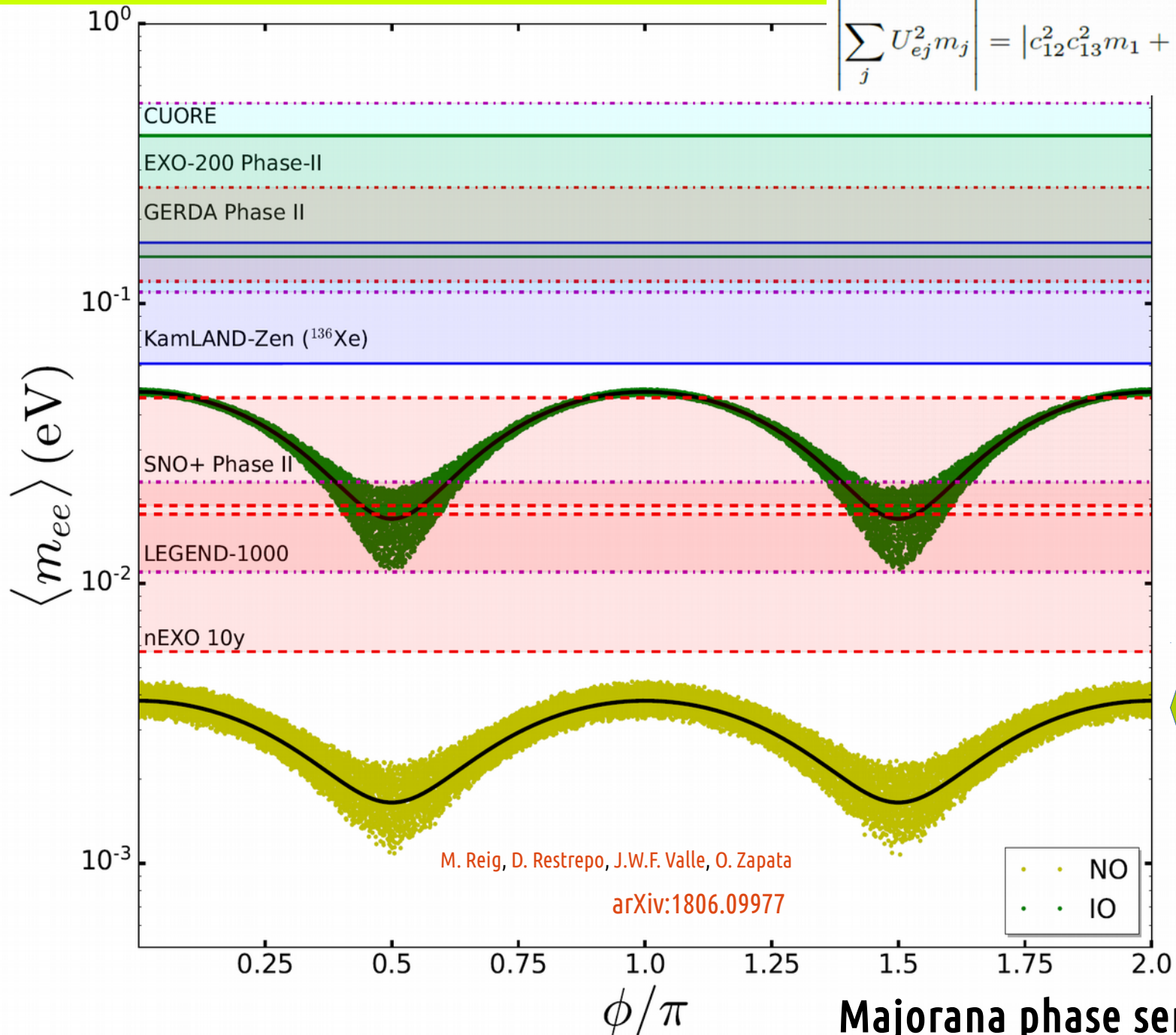


When one neutrino is massless

original symmetric form of lepton mixing matrix

Schechter & JV PRD22 (1980) 2227
Rodejohann, JV Phys.Rev. D84 (2011) 073011

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



lower-bound even for N.O.

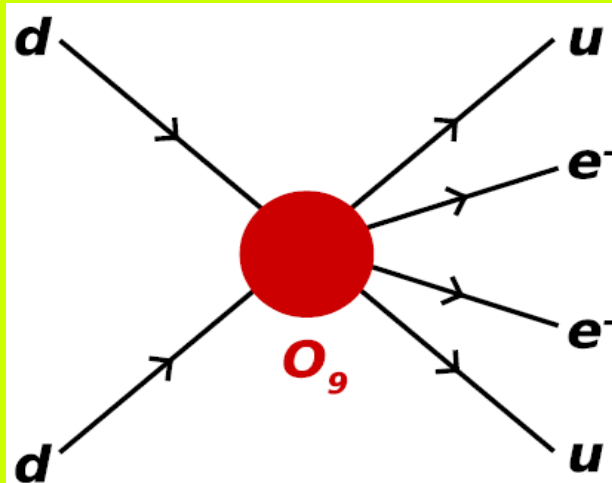
Majorana phase sensitivity ...

Schechter, Valle 82

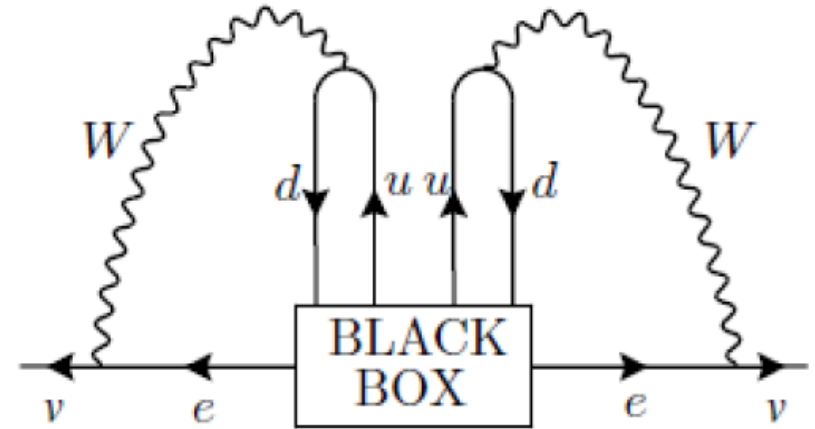
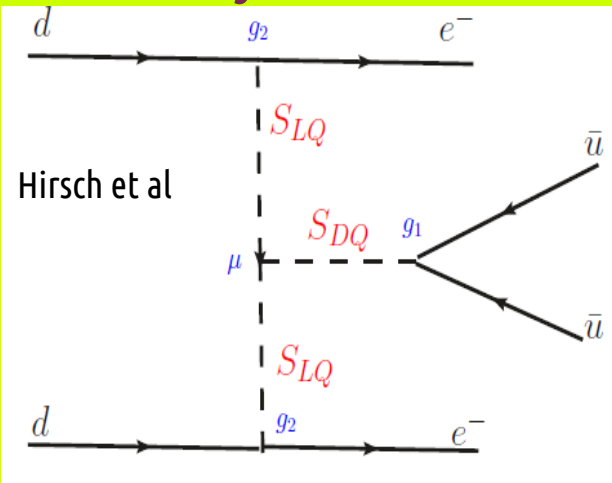
Lindner et al JHEP 1106 (2011) 091

Hirsch et al Phys.Lett. B781 (2018) 302-305

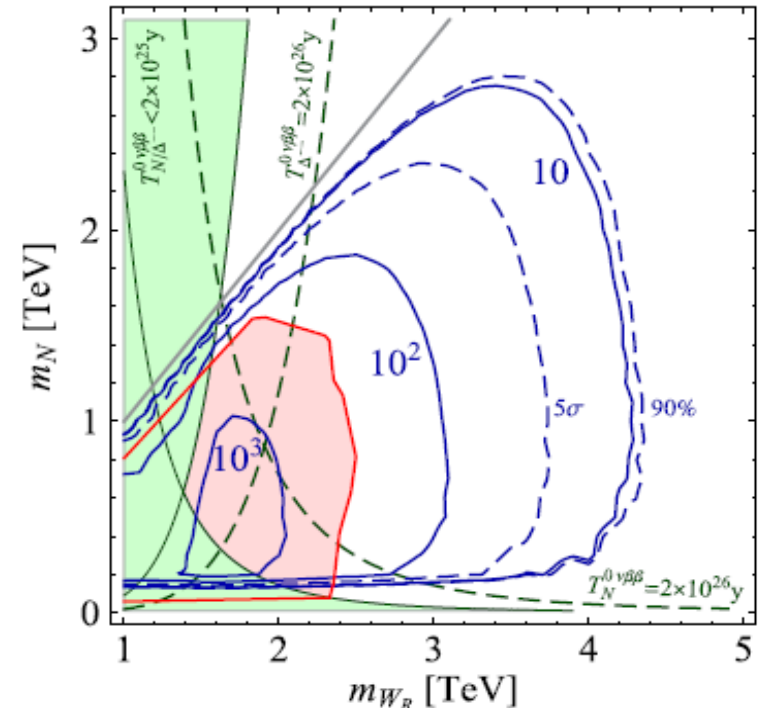
Short range mechanisms



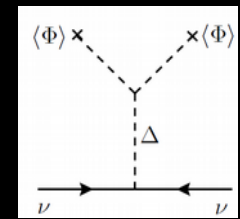
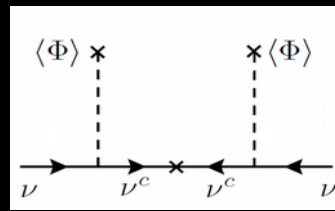
Heavy mediators



LHC PHYSICAL REVIEW D 86, 055006 (2012)



Origin of neutrino mass

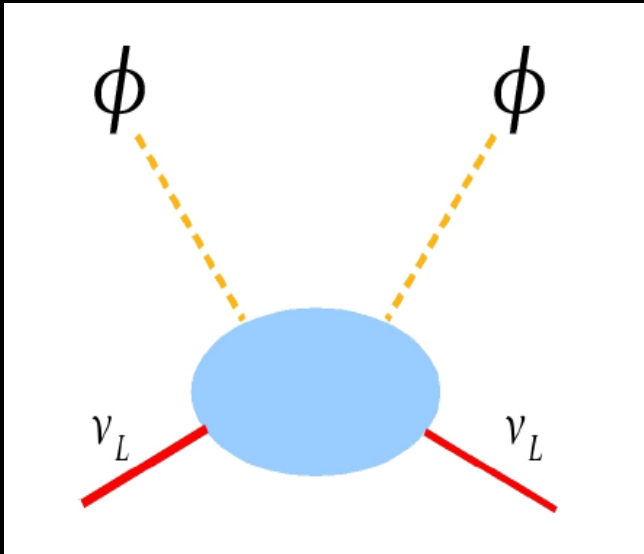


TYPE I

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

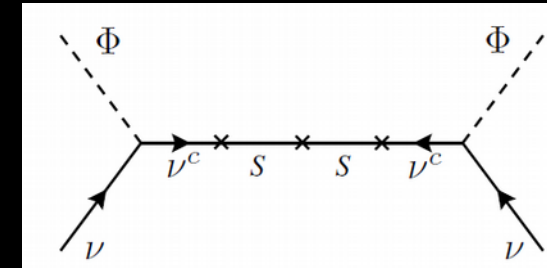
$$v_3 v_1 \sim v_2^2$$

coefficient
 mechanism
 scale
 flavor structure

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

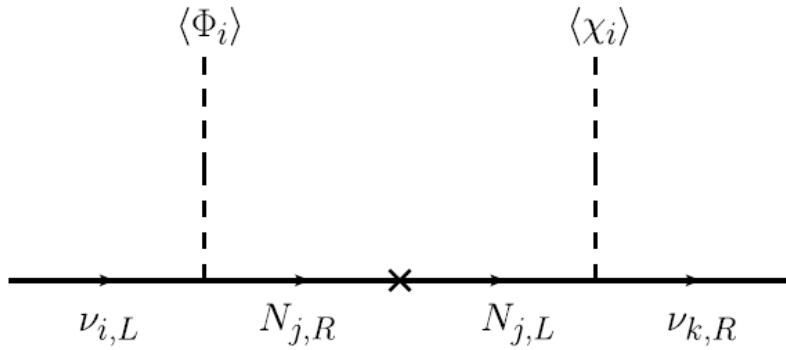
LOW-SCALE SEESAW

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



rectangular lepton mixing: R's decouple from oscillation \rightarrow unitarity violation
 if some R's remain light they may take part in oscillation (eV-scale steriles)

Seesawing a la Dirac



type 1

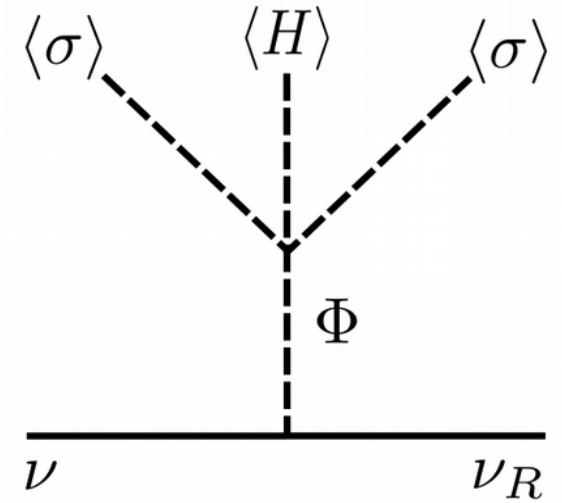
Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

Symmetry protects small neutrino mass

Phys.Rev. D98 (2018) 035009

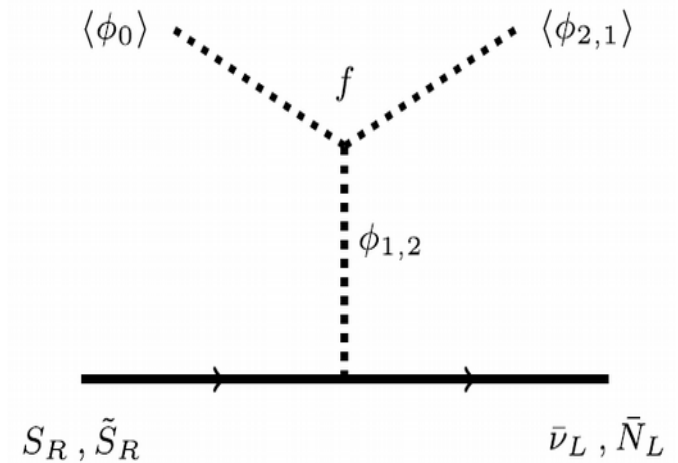
Phys.Lett. B781 (2018) 122-128



type 2

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



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

Phys.Lett. B755 (2016) 363-366

radiative neutrino mass

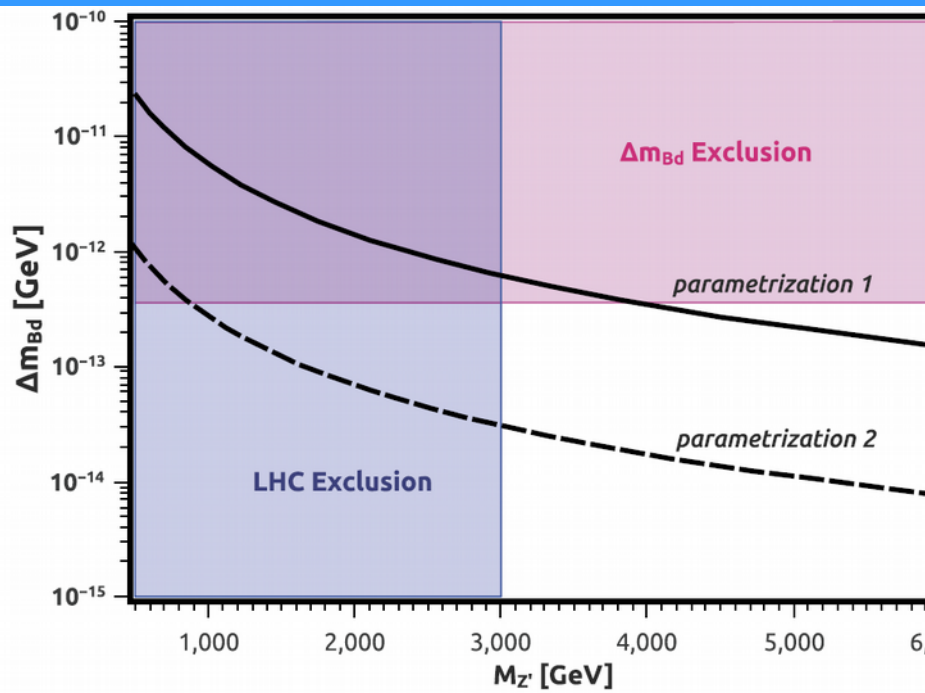
many low-scale neutrino mass schemes ...

arXiv:1404.3751

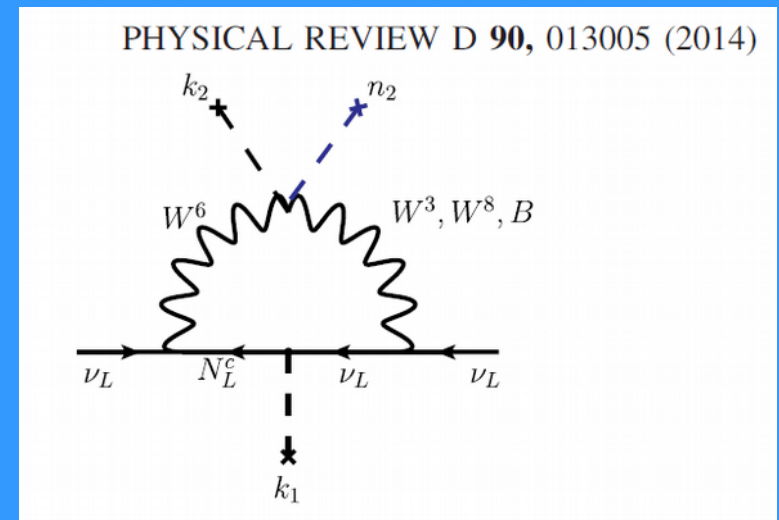
331 EW theory # families = # colours

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

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



Gauge vs Higgs



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



understanding flavor is an open question

does the Cabibbo angle
play a special role?

Phys.Rev. D86 (2012) 051301

Phys.Lett. B748 (2015) 1-4

why lepton
mixing so special
w.r.t. CKM?

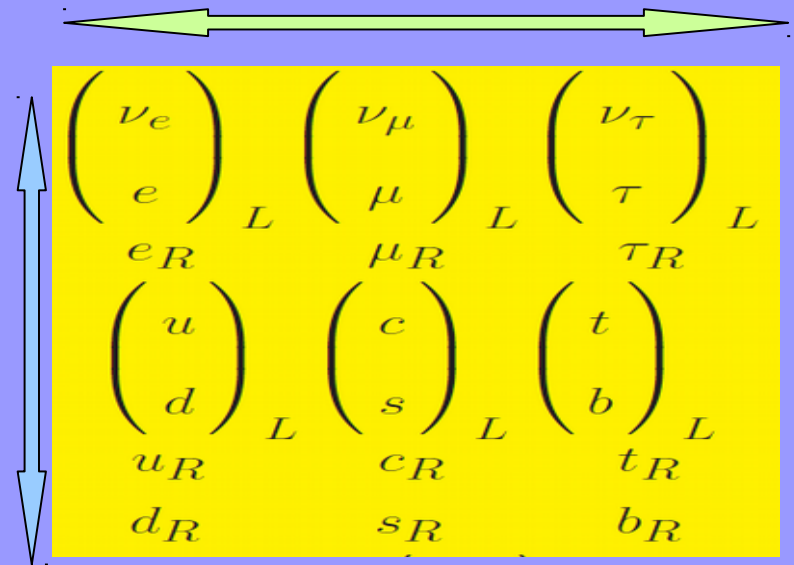
SM lacks an organizing principle

Simplest flavor symmetry

A4

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

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

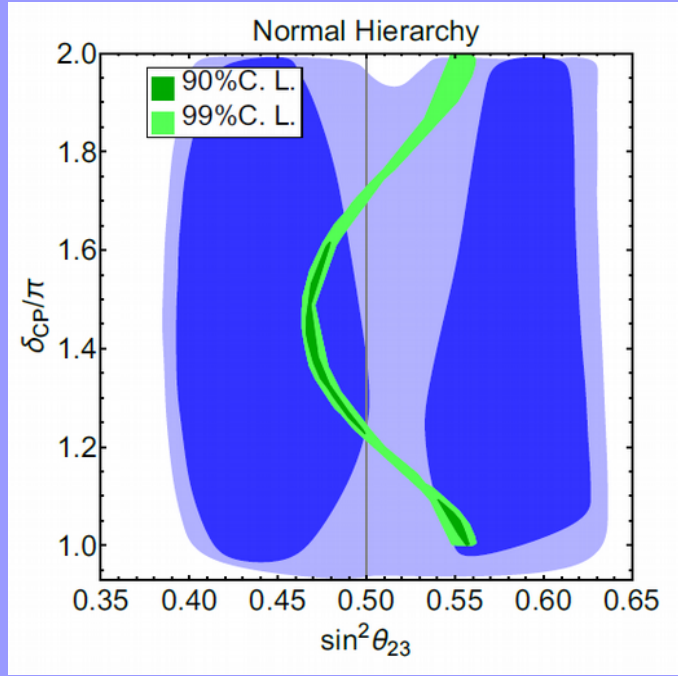


Babu-Ma-Valle PLB552 (2003) 207

Hirsch et al PRD69 (2004) 093006

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

Constrained global fit
1708.03290
Phys.Lett. B774 (2017) 179-182

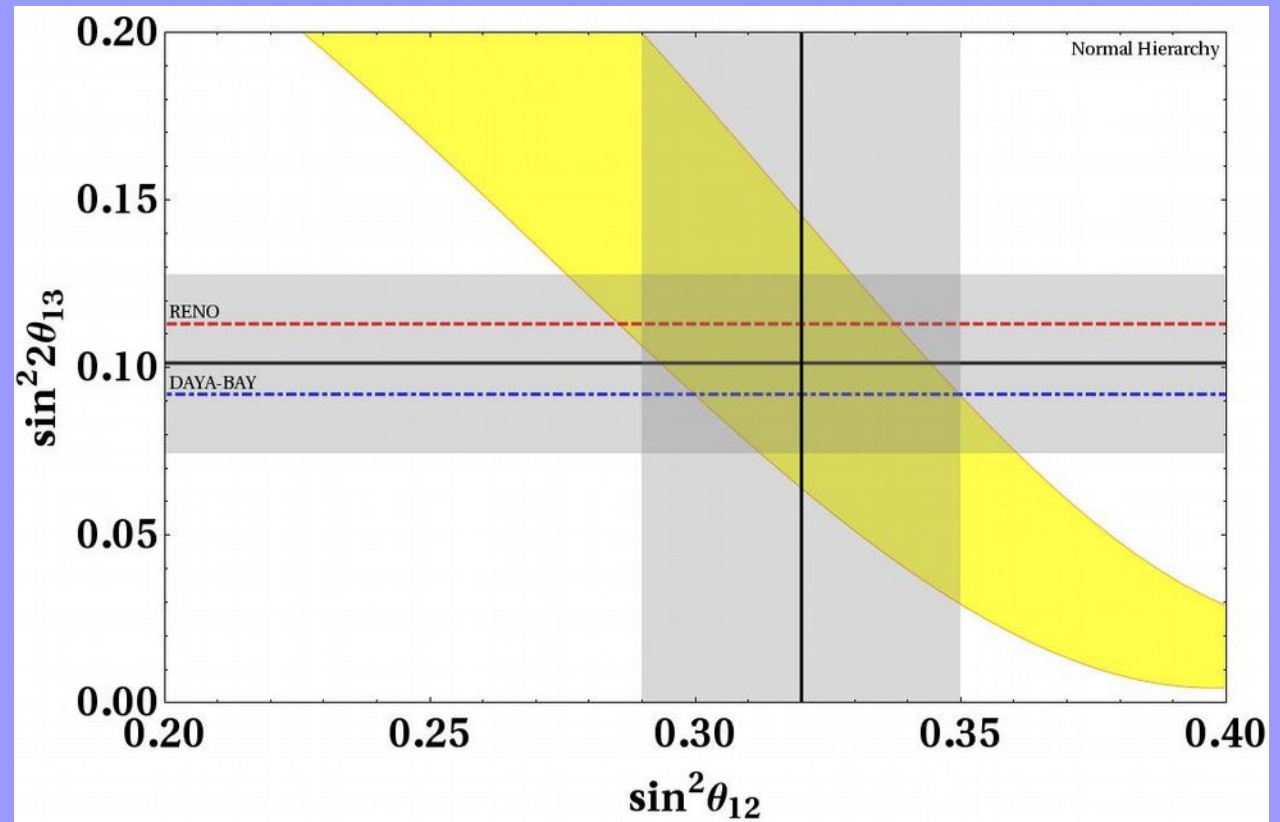


Probed at LBL experiments, e.g. DUNE...

Flavor correlations

Boucenna et al

Phys.Rev. D86 (2012) 073008



P Chen et al

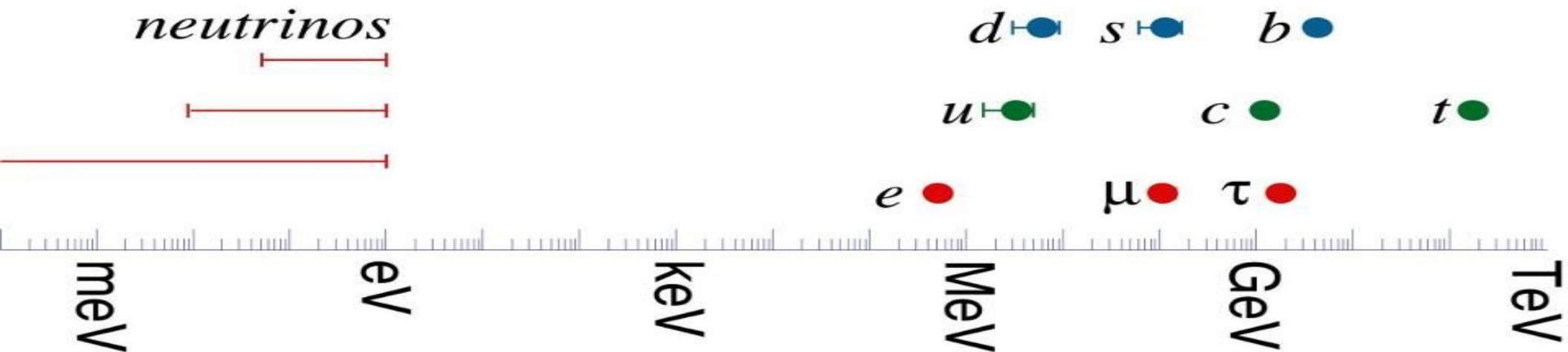
Phys.Lett. B753 (2016) 644-652

Phys.Rev. D94 (2016) 033002

JHEP 1807 (2018) 077

arXiv:1806.03367 Revamped TBM ansatz

CP flavor approach



from oscillations to charged fermion masses

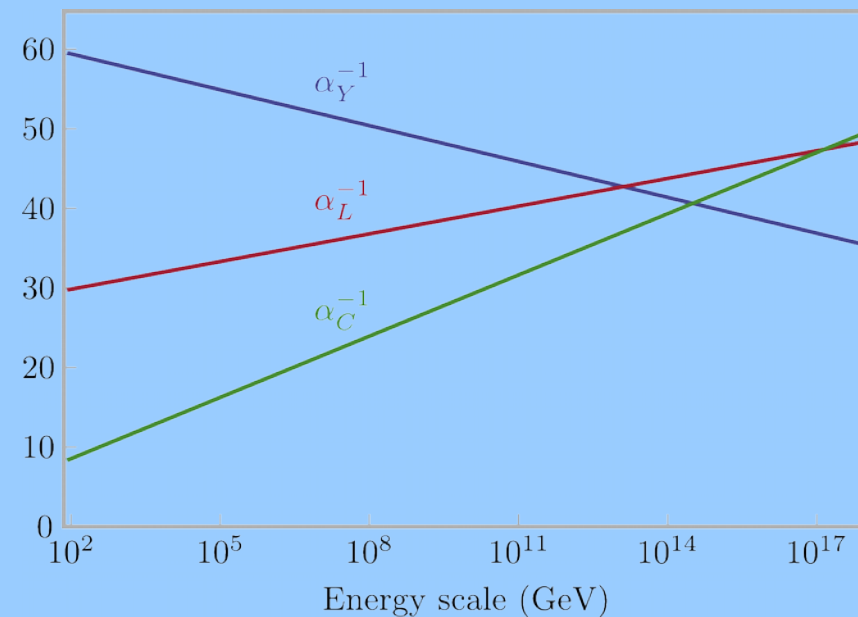
- Morisi et al Phys.Rev. D84 (2011) 036003
- King et al Phys. Lett. B 724 (2013) 68
- Morisi et al Phys.Rev. D88 (2013) 036001
- Bonilla et al Phys.Lett. B742 (2015) 99

**Golden Q-L
unification**

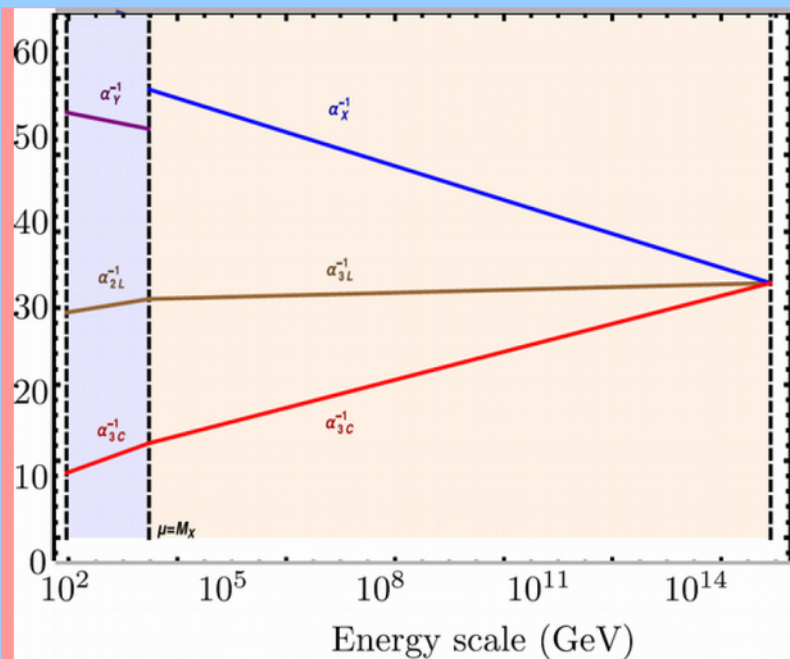
$$\frac{m_\tau}{\sqrt{m_e m_\mu}} \approx \frac{m_b}{\sqrt{m_d m_s}}$$

Standard model

a near miss ...



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



neutrinos & unification

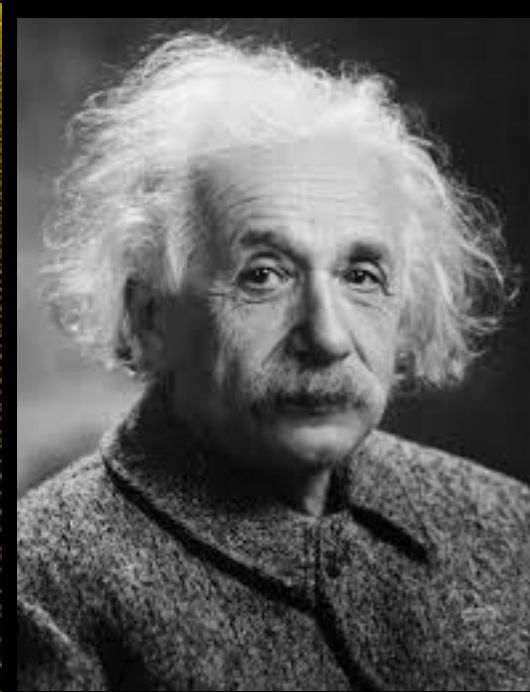
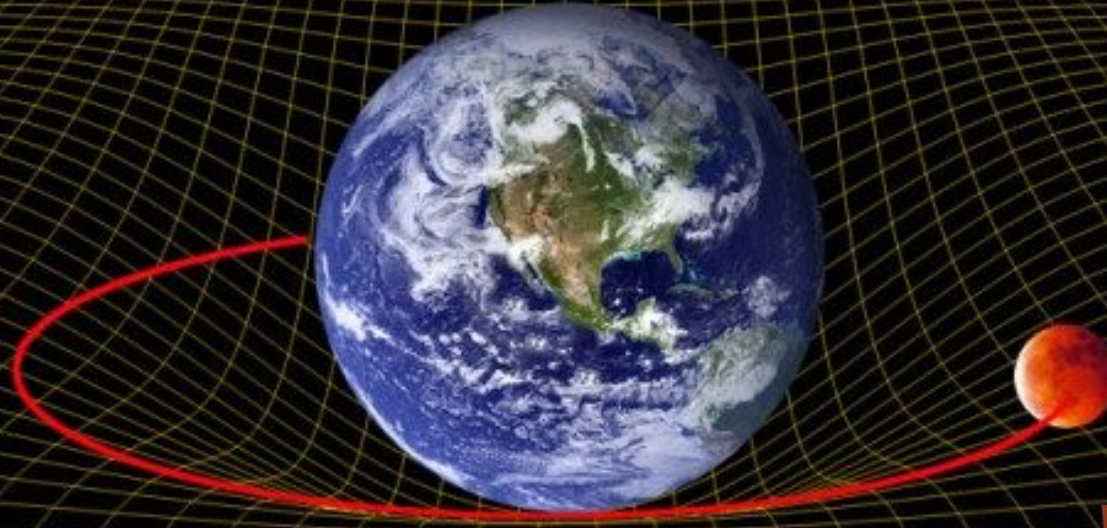
the physics responsible for neutrino masses
may also induce gauge coupling unification

E(6) F-theory GUT

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

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

including
Gravity



new dimensions?

Chen et al arXiv:1509.06683

JHEP01(2016)007

neutrinos in ToE



neutrino flavor predictions from Warped SM

:Chen et al
JHEP01(2016)007

mass hierarchies from geometry

→ angles related by symmetry

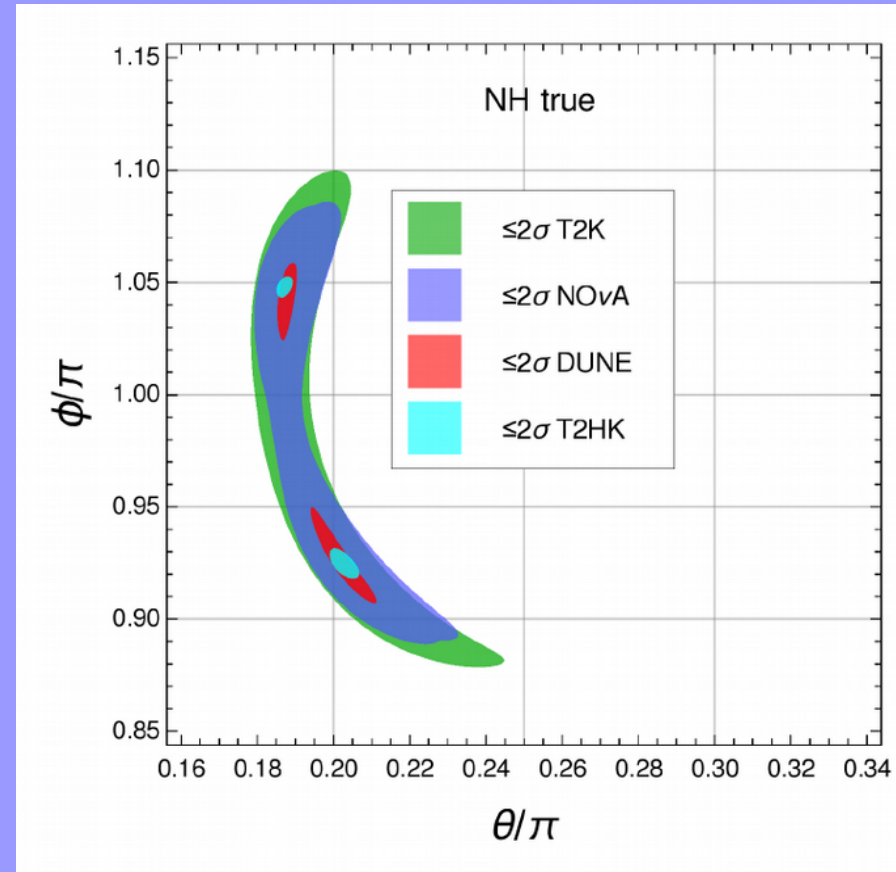
$$\sin^2 \theta_{12} = \frac{1}{2 - \sin 2\theta_v \cos \phi_v}$$

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

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

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

Constrained global fitting



Predictions for LBL experiments

Phys. Rev. D95 (2017) 095030

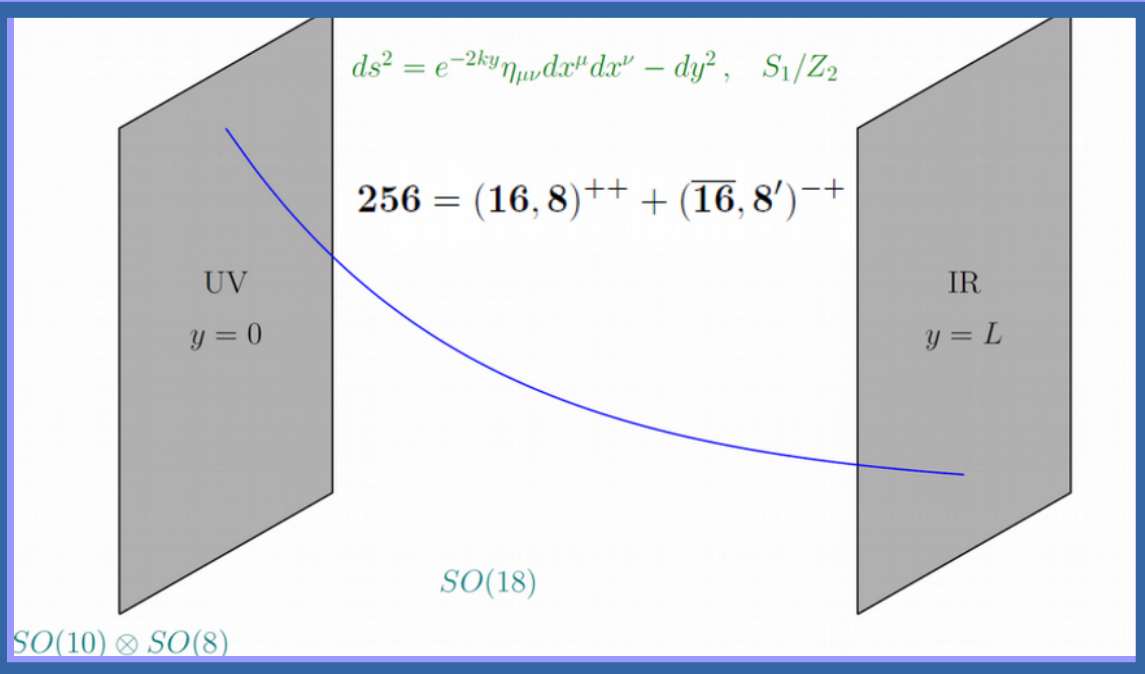
Phys.Lett. B771 (2017) 524

unifying forces & families

inspired by beauty of neutrinos in SO10

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

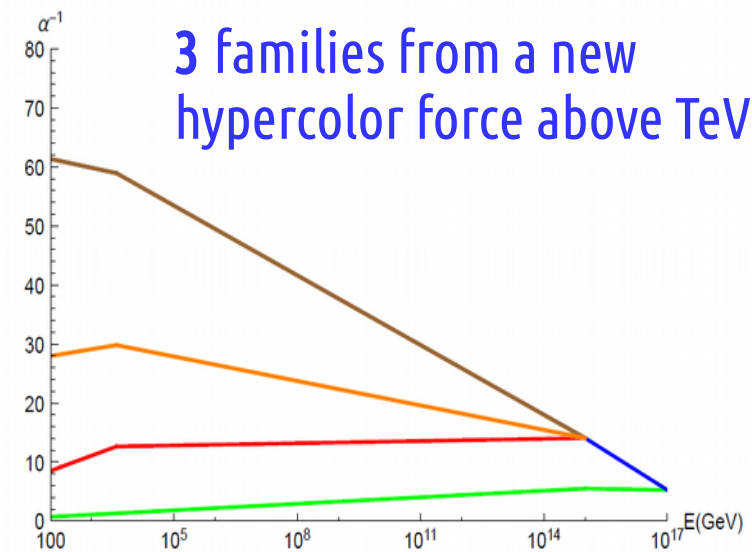
Reig, Valle, Vaquera-Araujo, Wilczek
Phys.Lett. B774 (2017) 667-670



promote M4 to AdS5 & use orbifold BC to decouple mirrors

Reig, JV, Wilczek
arXiv:1805.08048

$$SO(10) \times SO(8) \rightarrow SO(10) \times SO(5)_{HC}$$

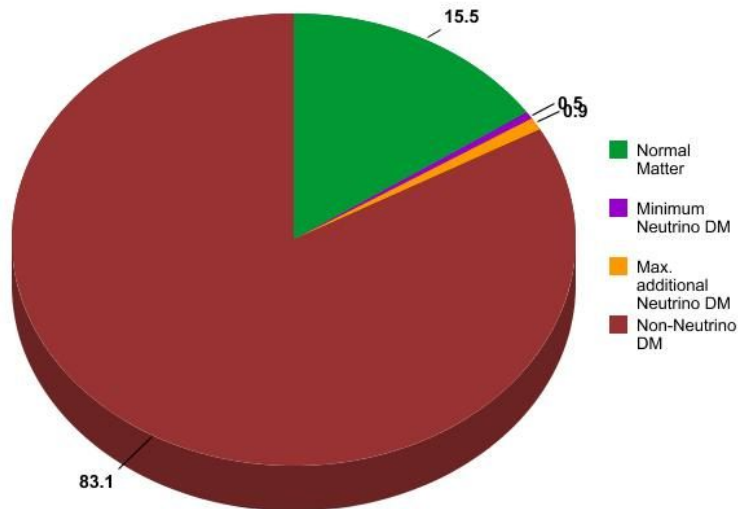


	q_L	u_R	d_R	l_L	e_R	ν_R	Φ^u	Φ^d	Ψ^u	Ψ^d	σ	ρ
$SU(3)_c$	3	3	3	1	1	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	2	2	2	2	1	1
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	0	0
$SO(3)_F$	3	3	3	3	3	3	5	5	3	3	5	1
$U(1)_{PQ}$	1	-1	-1	1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

SO(3) family symmetry

axion needed, with seesaw at PQ scale
Golden Q-L unification

The Universe's Matter



Created by Ethan Siegel

nu's at most 1% of DM, but can provide key to dark matter

e.g. **majoron** Berezhinsky, Valle 1993

metastable KeV warm dark matter

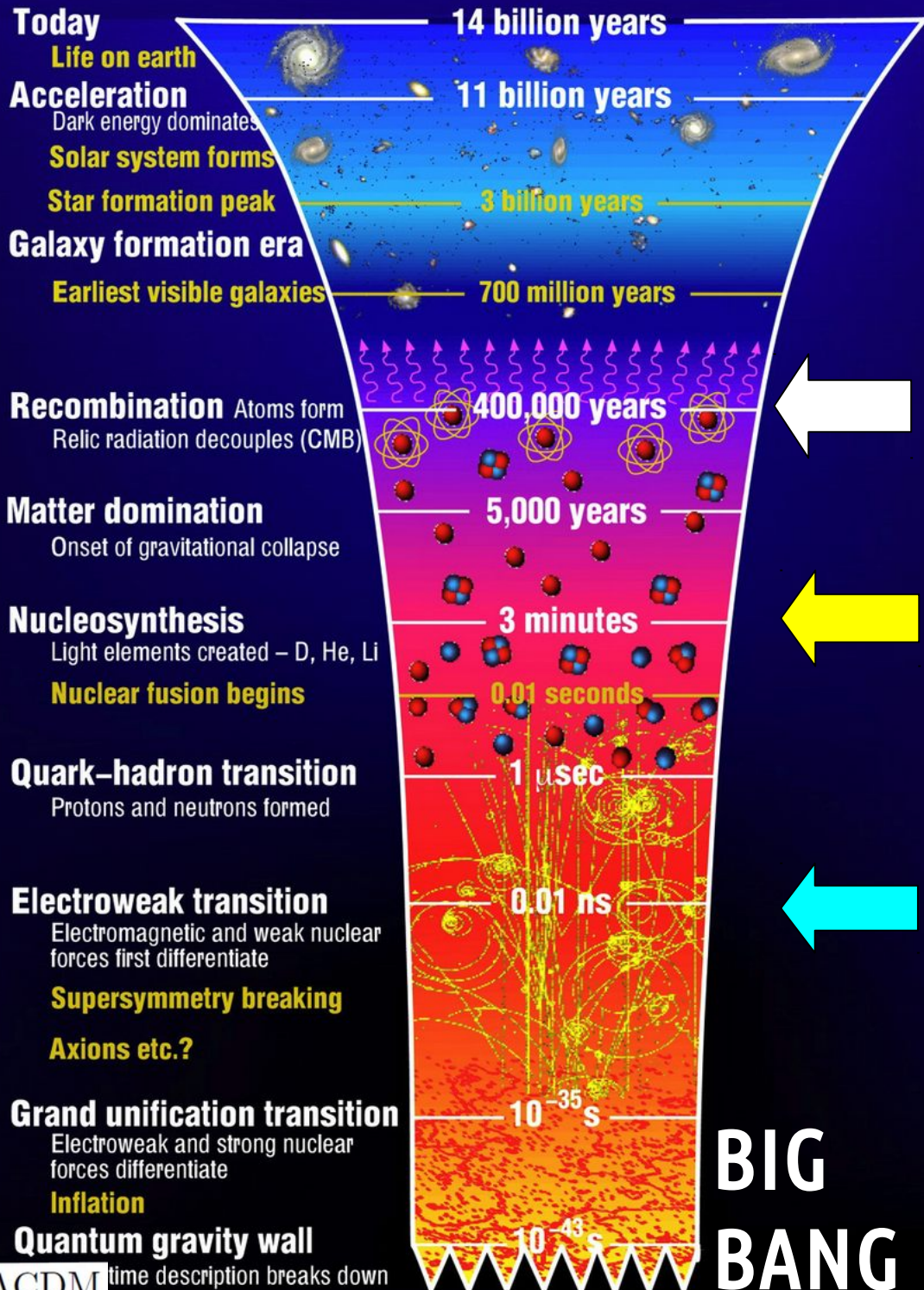
Lattanzi & Valle, PRL99 (2007) 121301

Bazzocchi & al JCAP 0808 (2008) 013

Esteves et al, PRD 82, 073008 (2010)

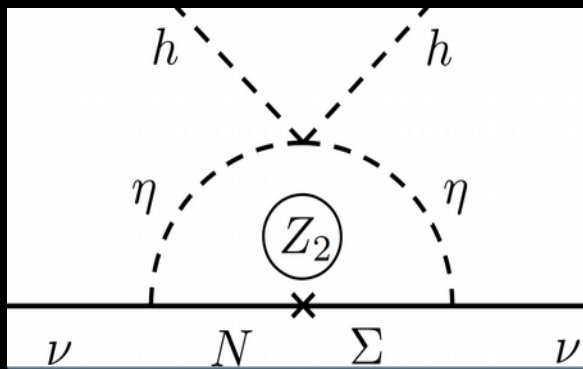
Lattanzi et al PRD88 (2013) 063528

Kuo et al 1803.05650



DWDM picture leads to a viable alternative to the Λ CDM

COLD WIMP dark matter



E Ma 2006 "scotogenic"

Hirsch et al JHEP 1310 (2013) 149

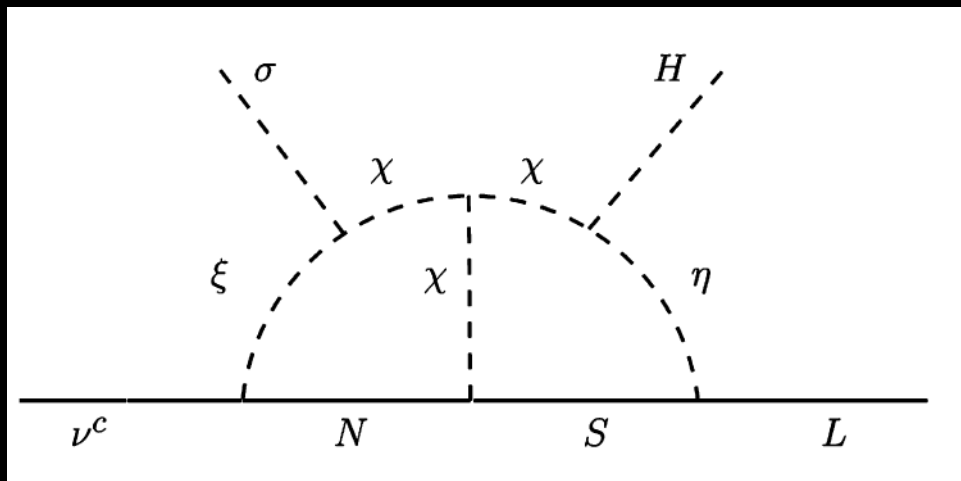
Merle et al JHEP 1607 (2016) 013

Diaz et al JHEP01(2016)007



dark matter emerges as radiative neutrino mass messenger

	Standard Model			Fermions		Scalars	
	L	e	ϕ	Σ	N	η	Ω
Generations	3	3	1	1	1	1	1
$SU(2)_L$	2	1	2	3	1	2	3
$U(1)_Y$	-1/2	-1	1/2	0	0	1/2	0
Z_2	+	+	+	-	-	-	+



Z_2 preserved by RGE

many variants, e.g.

Phys.Lett. B762 (2016) 214-218

dark matter as bound-state of neutrino mass messenger

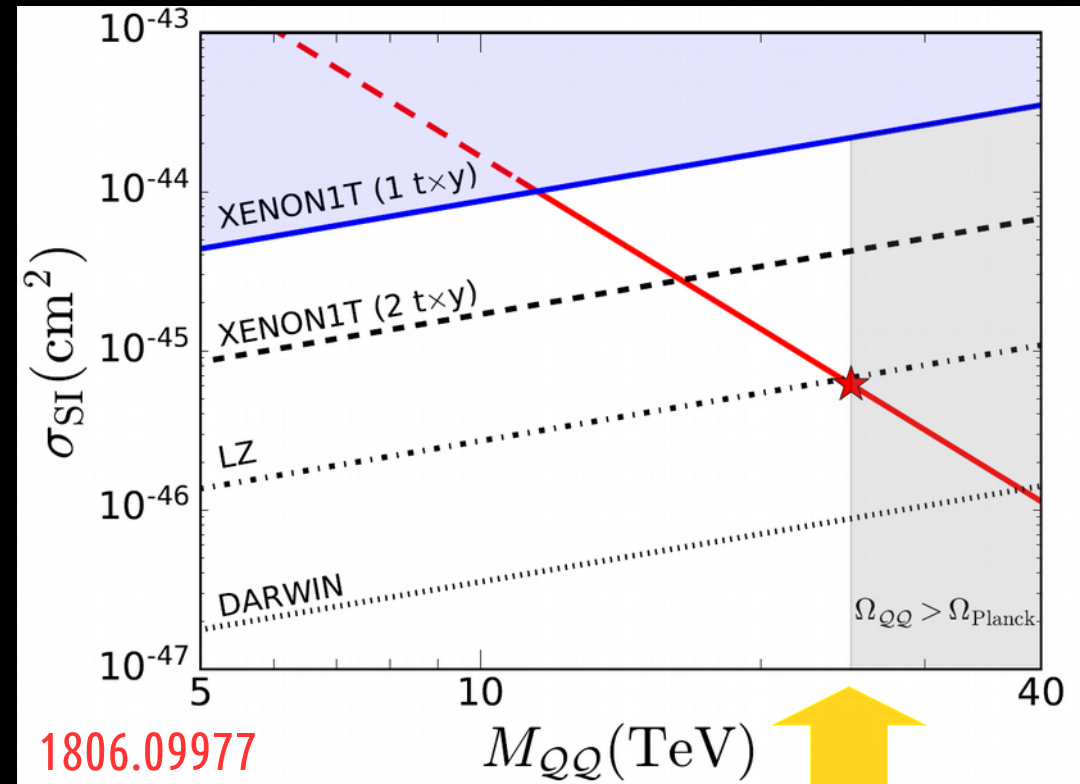
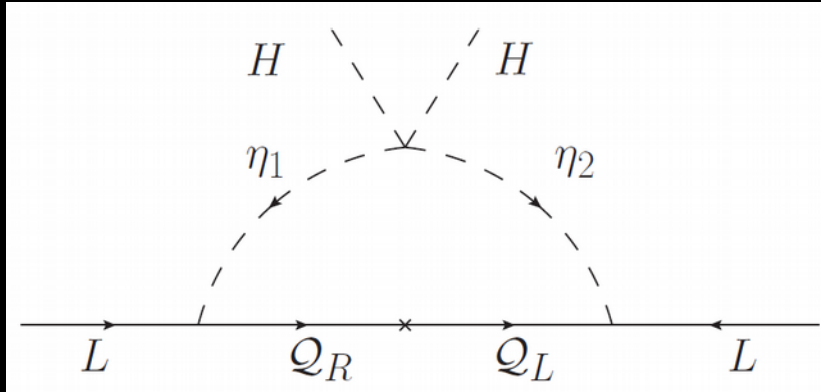


FIG. 2. Spin-independent cross section as a function of $M_{QQ} = 2M_Q$ (red). The star represents the mass required for a thermal bound state 25 TeV dark matter. Lower values can be probed by direct searches, the current bound is indicated in blue, while the black lines (dashed, dotted and dot-dashed) correspond to future sensitivities.

bright future oscillation physics

PhysRevD.92.053009
PhysRevLett.117.061804

Phys.Lett. 771 (2017) 524-531
Phys. Rev. D 96, 011303(R)
Phys.Rev. D95 (2017) 033005

neutrinos lie at the center of particle physics EWSB

New J. Phys. 19 (2017) 093005
Phys.Rev. D92 (2015) 075028

detecting messengers & measuring angles @ high energies

De Campos et al
Phys.Rev. D86 (2012) 075001

cosmology as emergent theory

DM can be warm & metastable, e.g. the majoron

JHEP 1105 (2011) 037

WIMP DM stability from flavor: discrete DM

Phys.Rev. D82 (2010) 116003

JHEP 1302(2013) 118

WIMP DM stability from Diracness arXiv:1606.04543

WIMP DM stability from gauge matter parity

Phys.Lett. B772 (2017) 825-83

majoron DM + inflation

Boucenna, Morisi, Shafi, Valle Phys.Rev. D90 (2014) 055023

adding dark energy

Smoot arXiv:1405.2776 etc etc

THE END