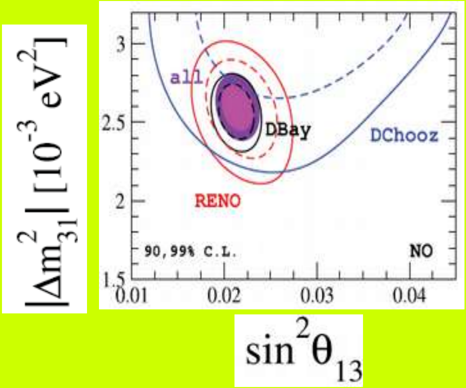
neutrinos updated

José W F Valle

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

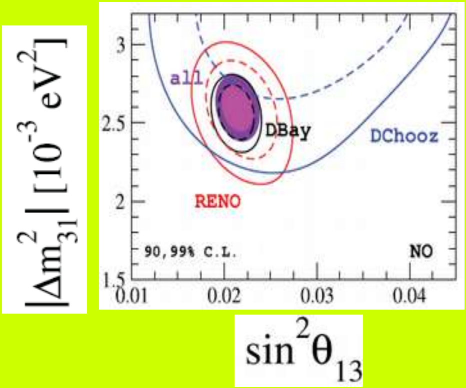
FLASY 2018 July2-5 2018 University of Basel

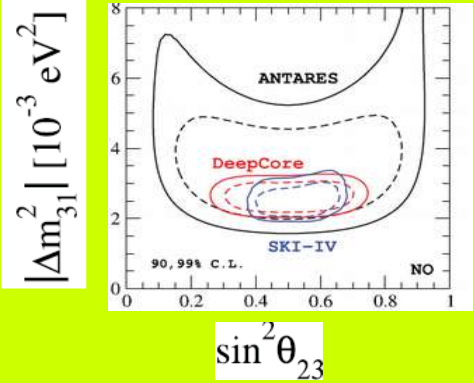
status of neutrino oscillations 2018

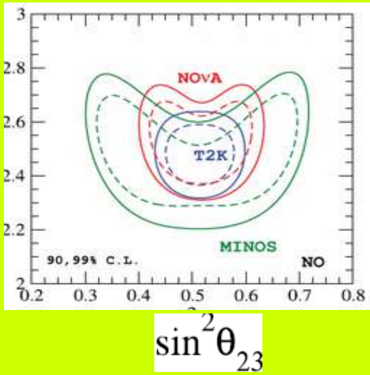


P.F. de Salas et al, PLB782 (2018) 633
https://globalfit.astroparticles.es/

status of neutrino oscillations 2018

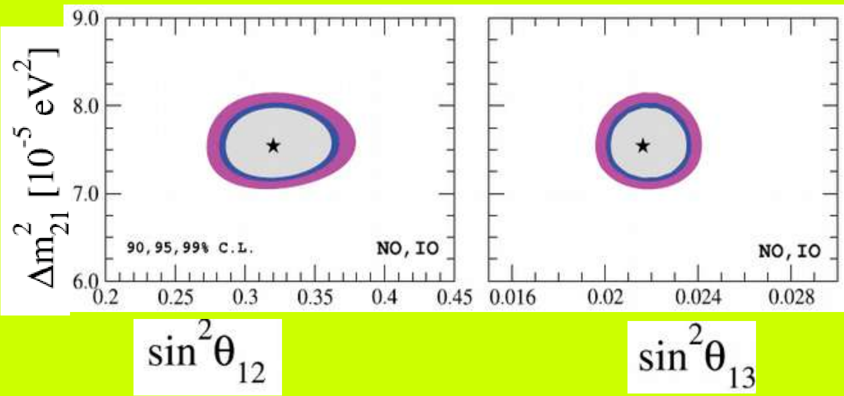


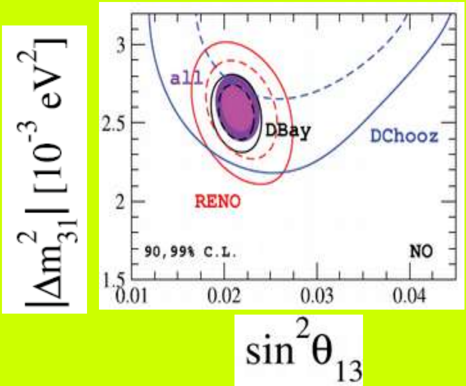


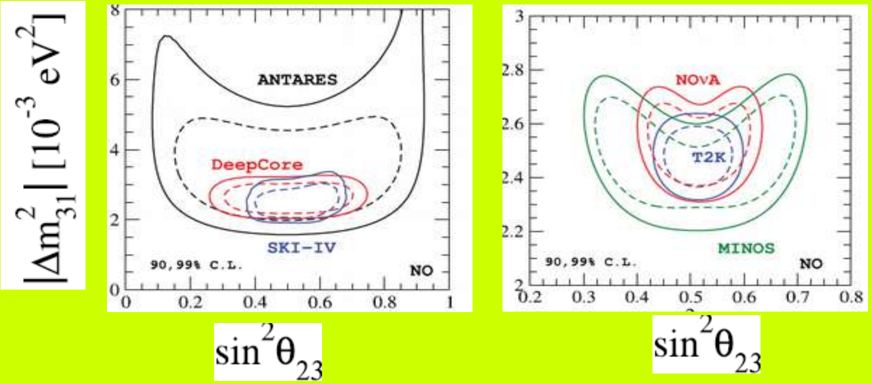


P.F. de Salas et al, PLB782 (2018) 633
https://globalfit.astroparticles.es/

status of neutrino oscillations 2018



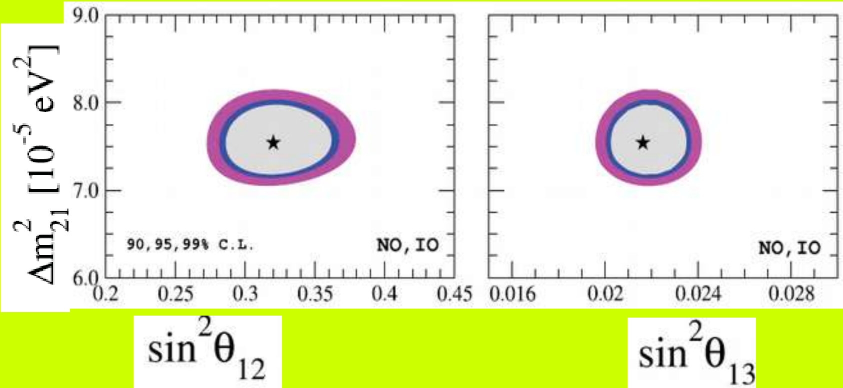


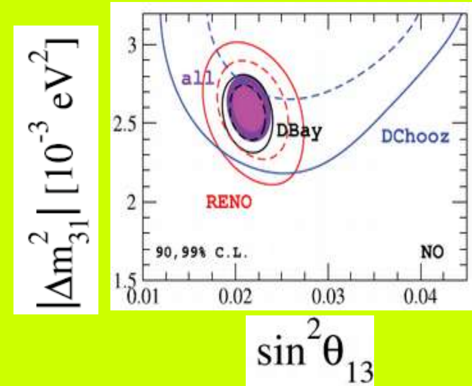


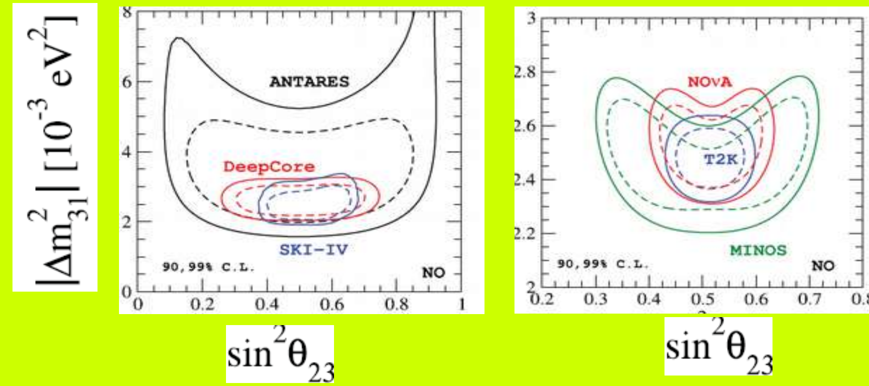
P.F. de Salas et al, PLB782 (2018) 633
https://globalfit.astroparticles.es/

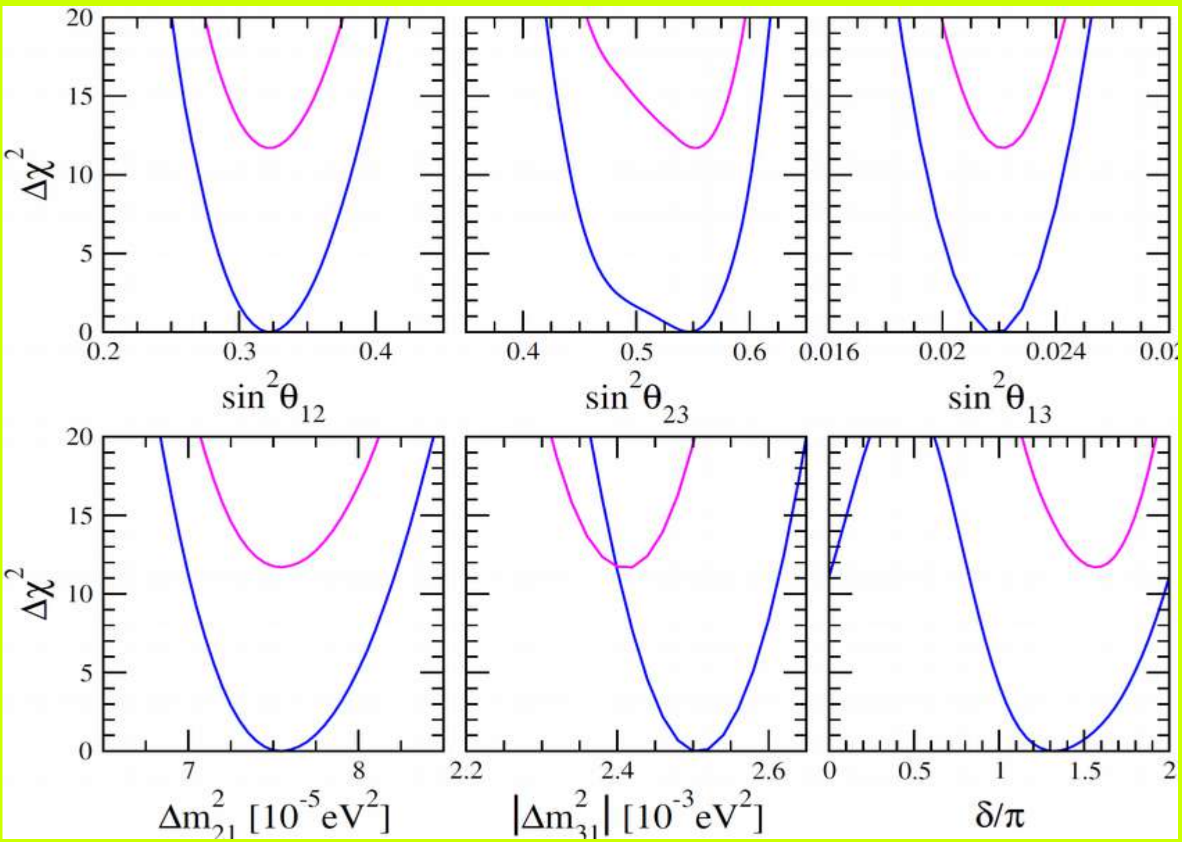
Consistent global picture
Good agreement

status of neutrino oscillations 2018









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

Consistent global picture
Good agreement

Beta & 0nu-doublebeta decay + cosmo

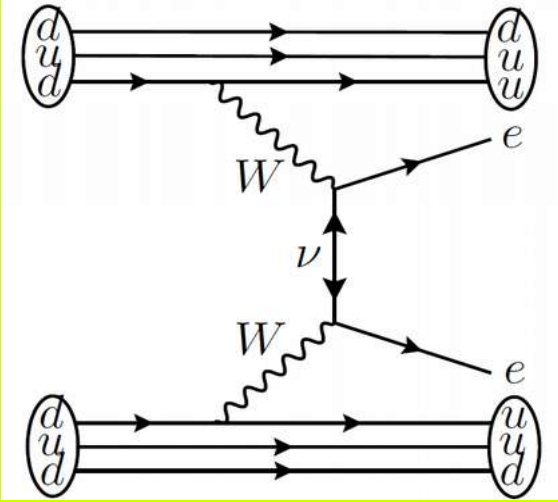
the neutrino mass scale

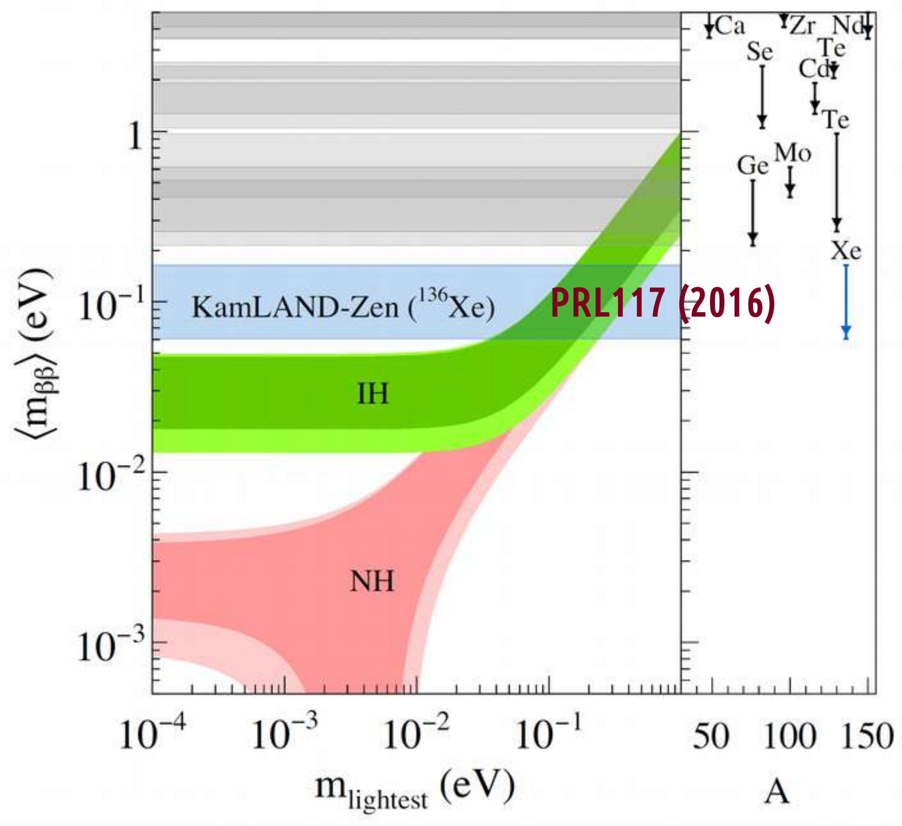
A.S. Barabash arXiv:1104.2714

Beta & 0nu-doublebeta decay + cosmo

the neutrino mass scale

A.S. Barabash arXiv:1104.2714



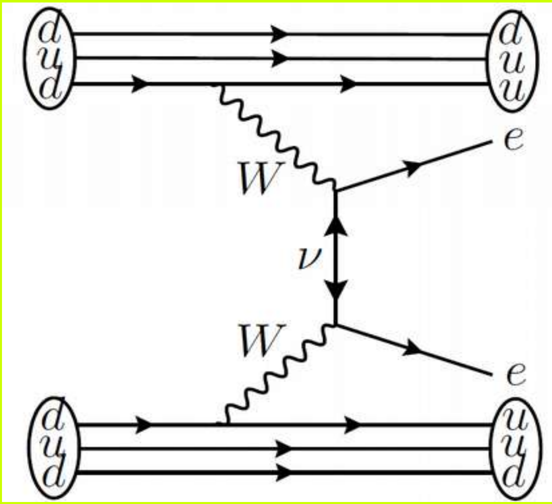


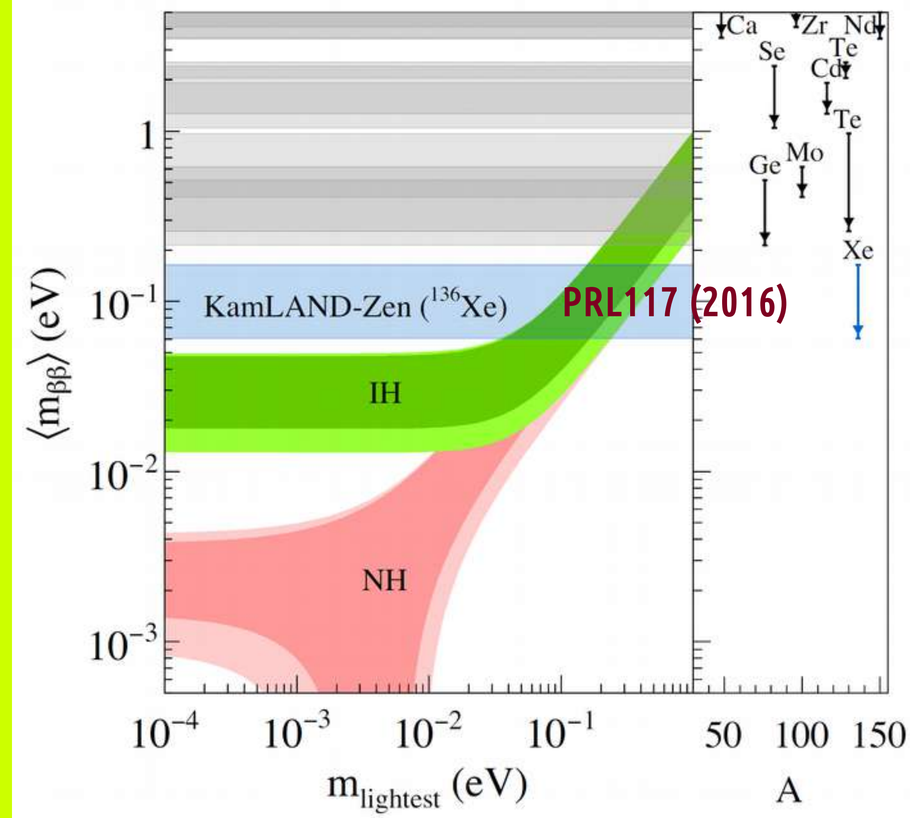
nEXO, **CUORE** , LEGEND (nGERDA/Majorana) ...

Beta & 0nu-doublebeta decay + cosmo

the neutrino mass scale

A.S. Barabash arXiv:1104.2714





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

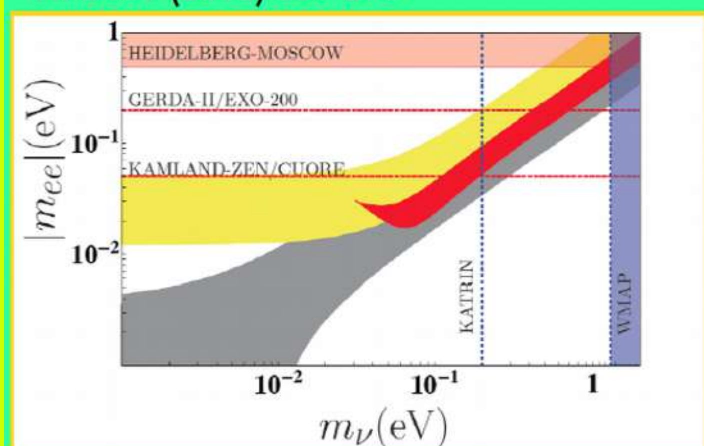
lower bounds even for normal ordering

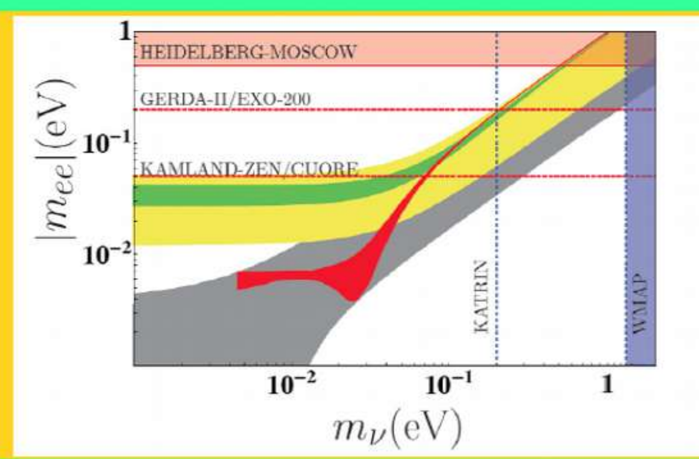
Dorame et al

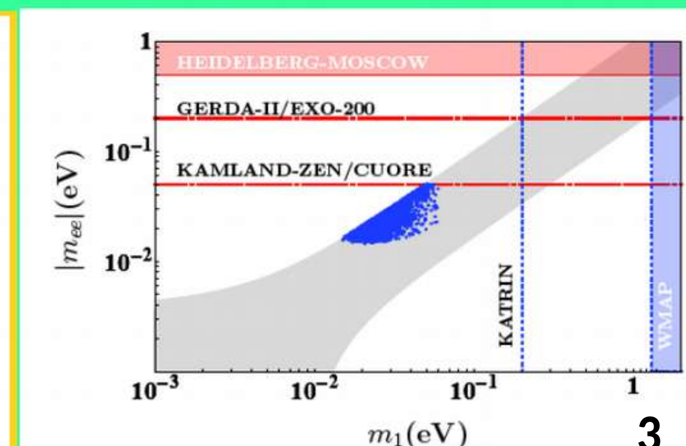
NPB861 (2012) 259-270

Dorame et al
PhysRevD.86.056001

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







sensitive to Majorana phase in lepton mixing matrix ...

original symmetric form

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

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

M. Reig, D. Restrepo, J.W.F. Valle, O. Zapata

arXiv:1806.09977

sensitive to Majorana phase in lepton mixing matrix ...

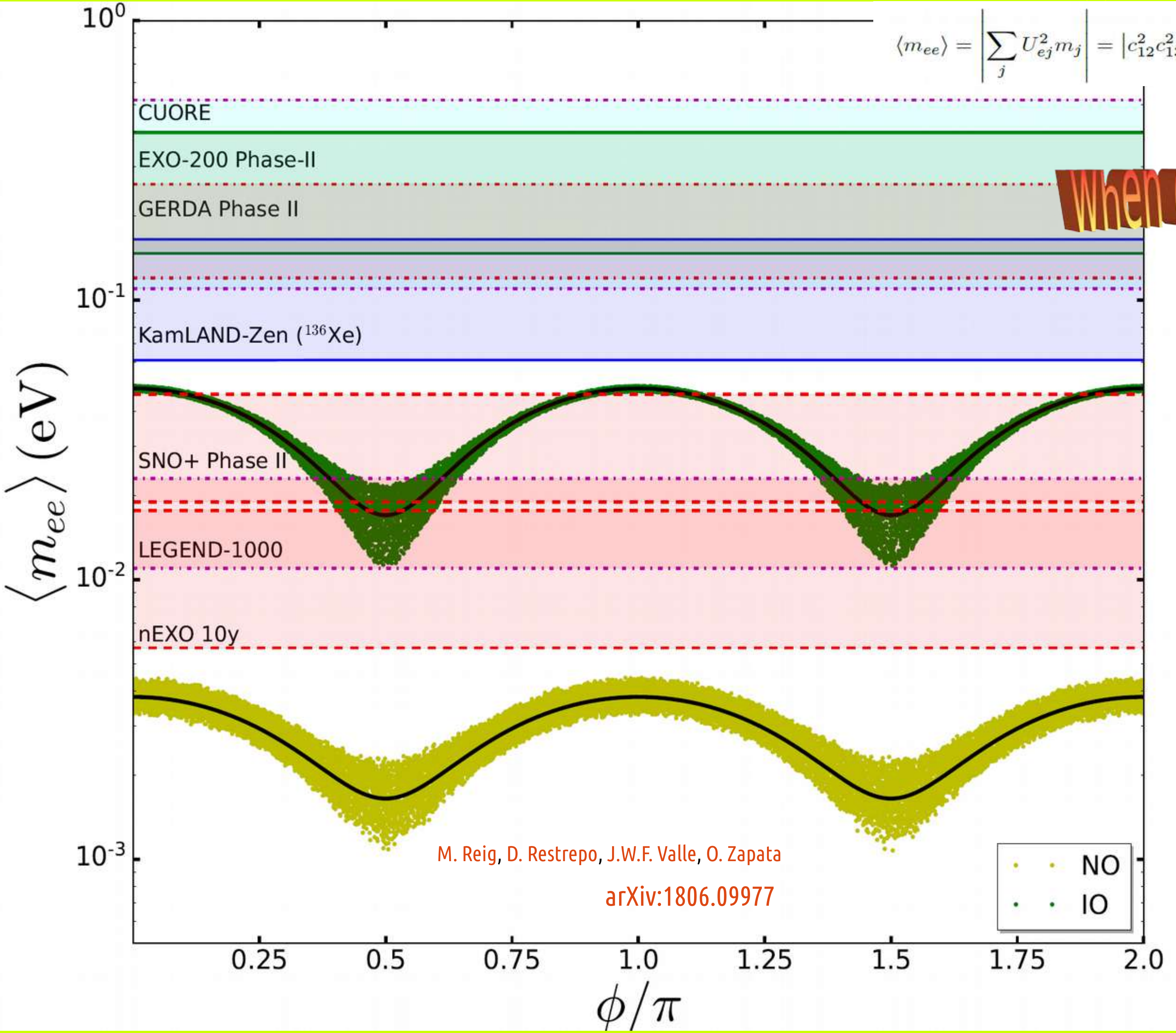
original symmetric form

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

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

When one neutrino is massless

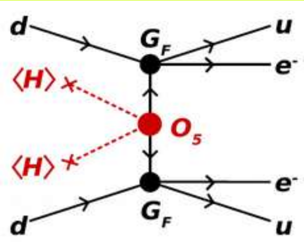
Lower bound even for NO

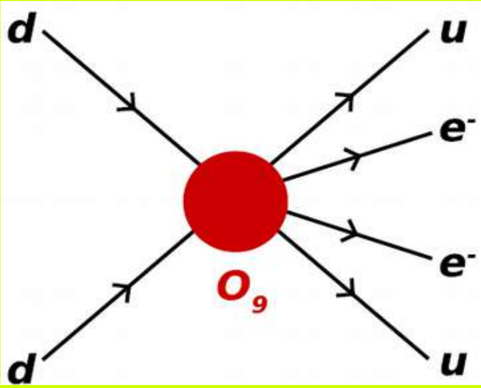


M. Reig, D. Restrepo, J.W.F. Valle, O. Zapata
arXiv:1806.09977

long vs short range

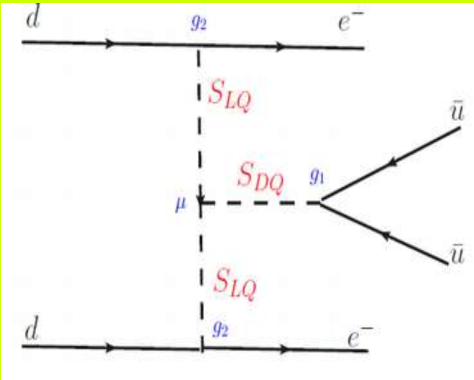
Pas et al



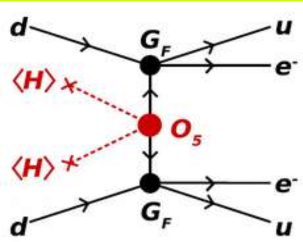


Heavy mediators

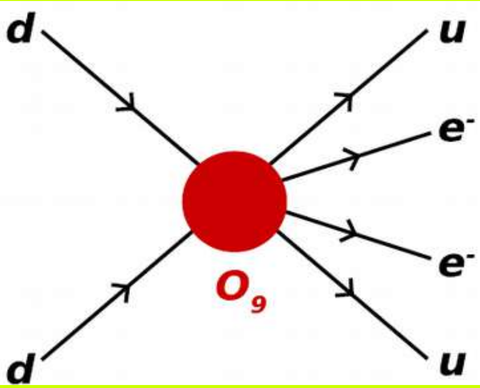
Hirsch et al



long vs short range

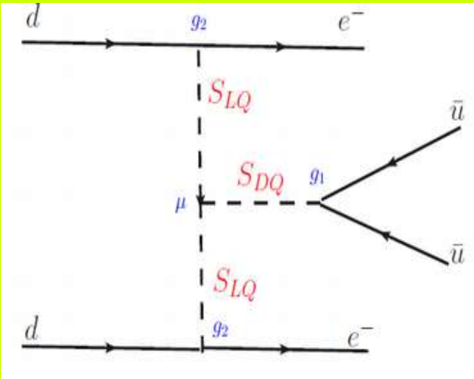


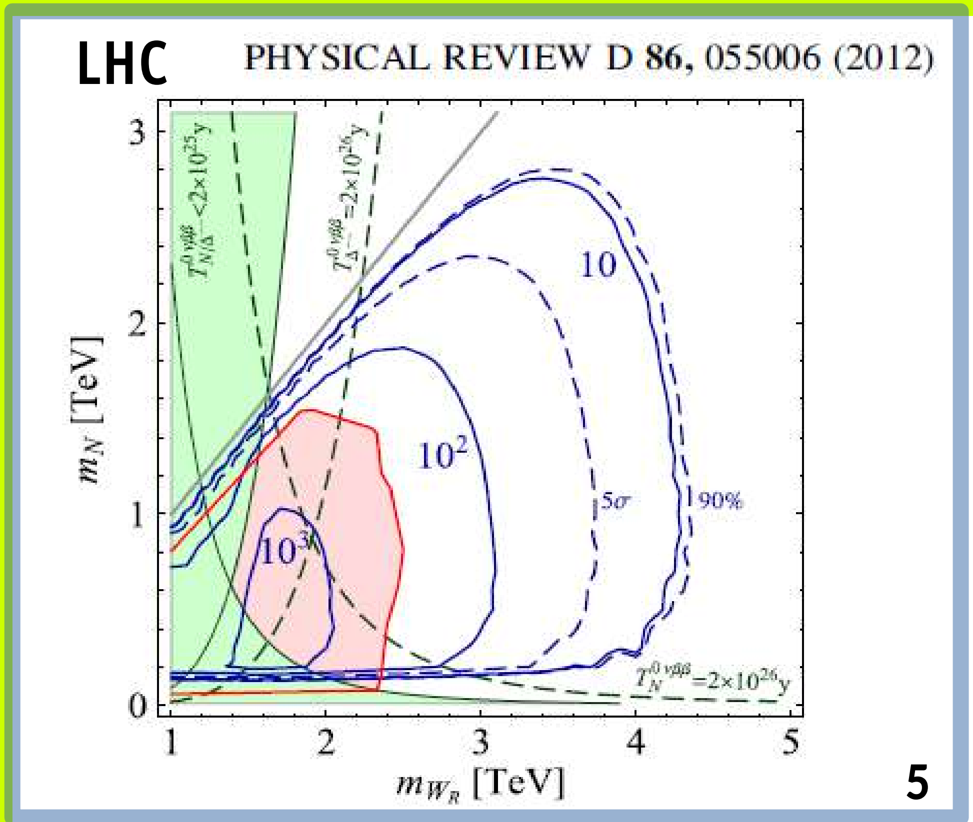
Pas et al



Heavy mediators

Hirsch et al



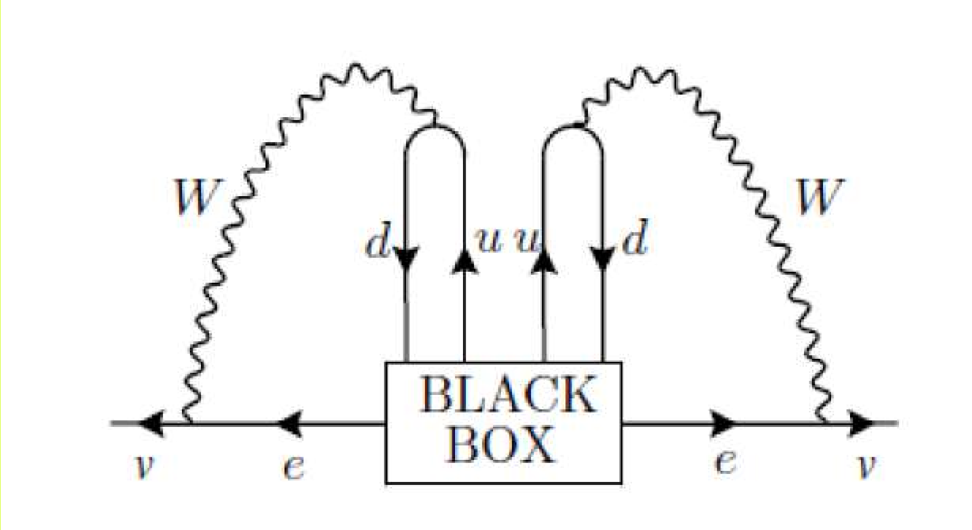


long vs short range

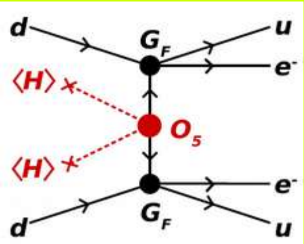
Significance

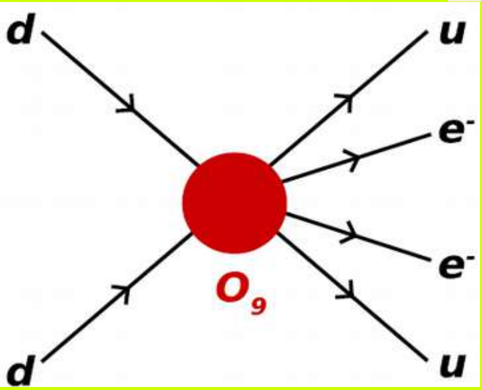
Schechter, Valle 82

Lindner et al JHEP 1106 (2011) 091



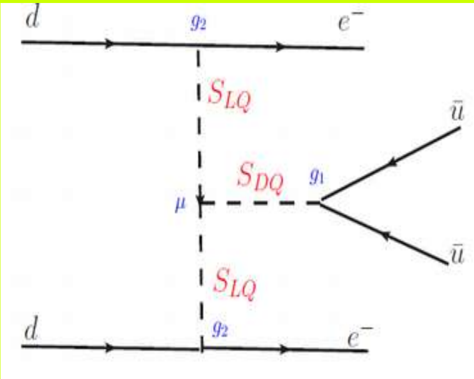
Pas et al





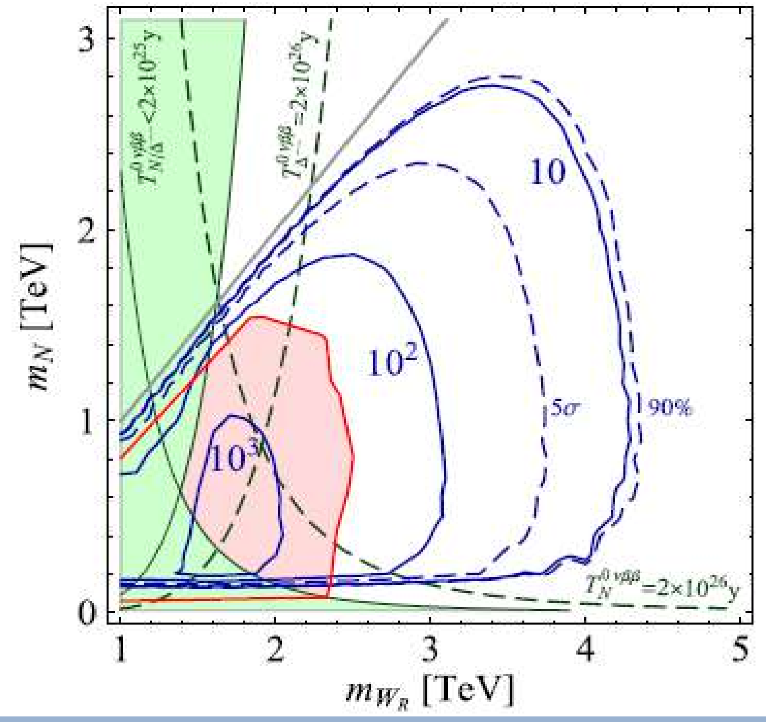
Heavy mediators

Hirsch et al

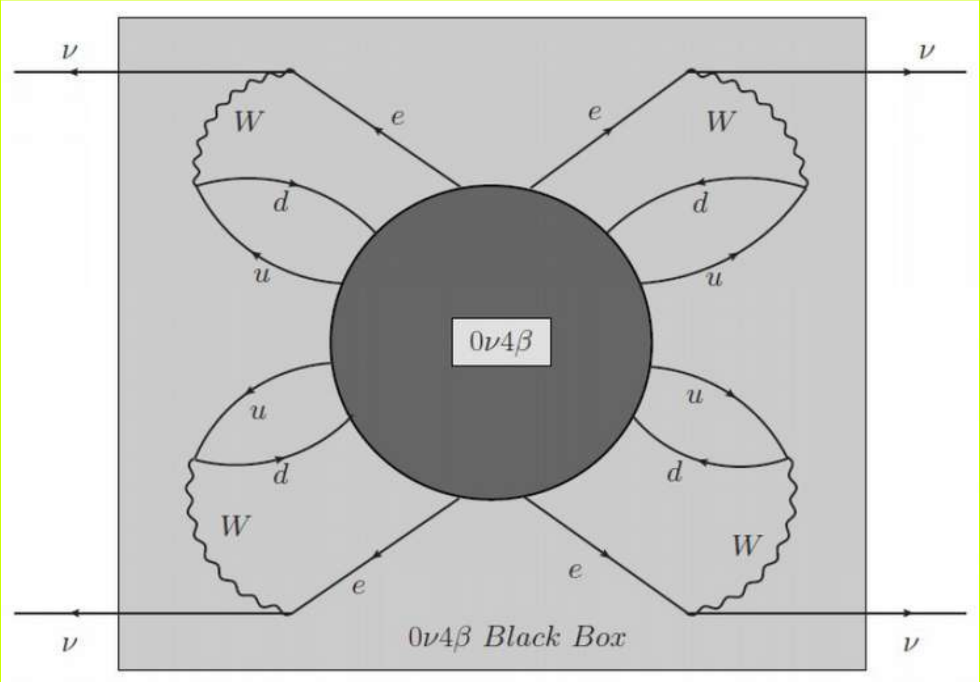


LHC

PHYSICAL REVIEW D **86**, 055006 (2012)



What if we do not observe 0nu double beta decay?



Discrete lepton number: quarticity Z4

Centelles-Chulia et al

10.1016/j.physletb.2017.01.070

https://doi.org/10.1016/j.physletb.2018.01.014

allows quadruple beta decay even if neutrinos are Dirac
J. Heeck and W. Rodejohann

Hirsch et al
https://doi.org/10.1016/j.physletb.2018.03.073

Criterium for Diracness?

much progress but many open questions

does the Cabbibo 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?

Is there a flavor symmetry?

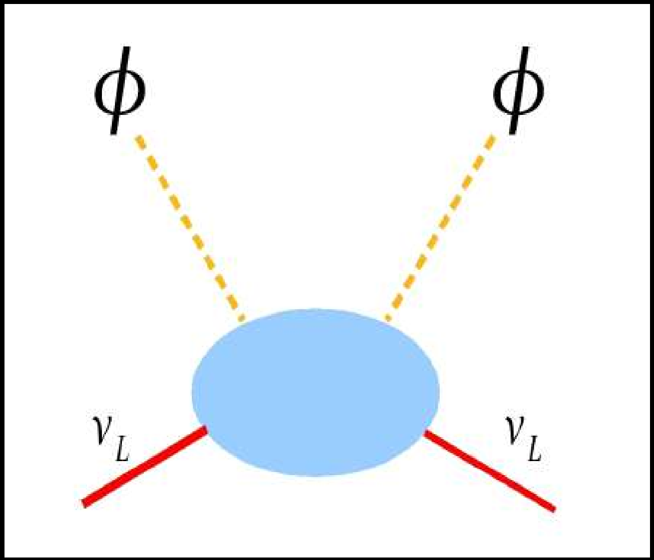
Is it common for leptons & quarks?

can one predict angles & phases?

Dirac or Majorana?

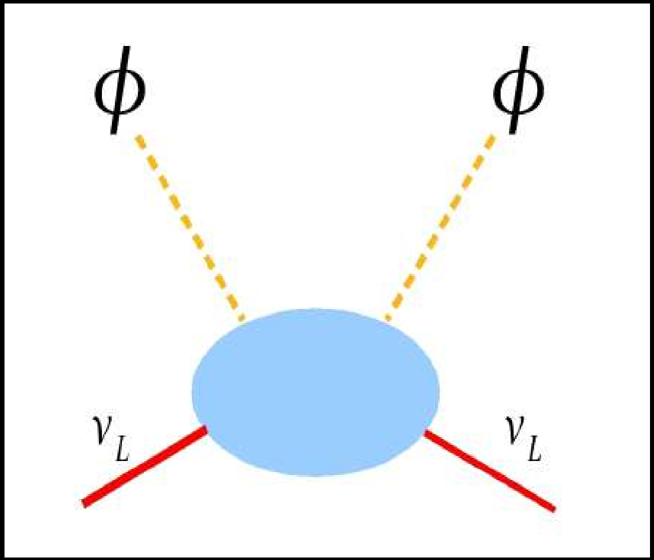
why so light?

Origin of neutrino mass



coefficient
mechanism
scale
flavor structure

Origin of neutrino mass



Seesaw

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

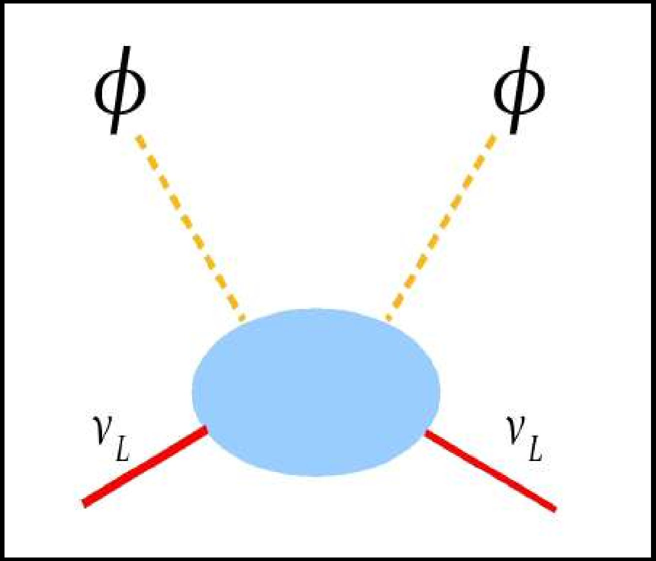
coefficient

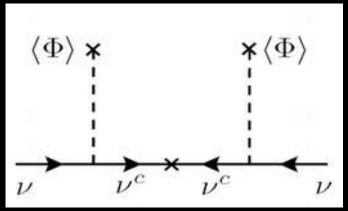
mechanism

scale

flavor structure

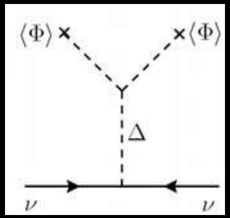
Origin of neutrino mass





TYPE I

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



TYPE II

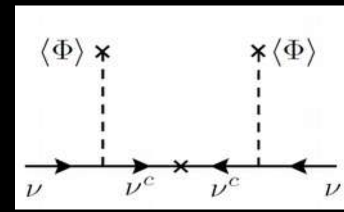
Schechter-Valle, 80 & 82

seesaw

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

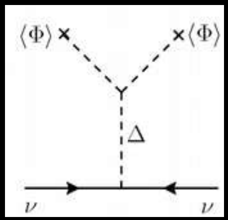
coefficient
mechanism
scale
flavor structure

Origin of neutrino mass



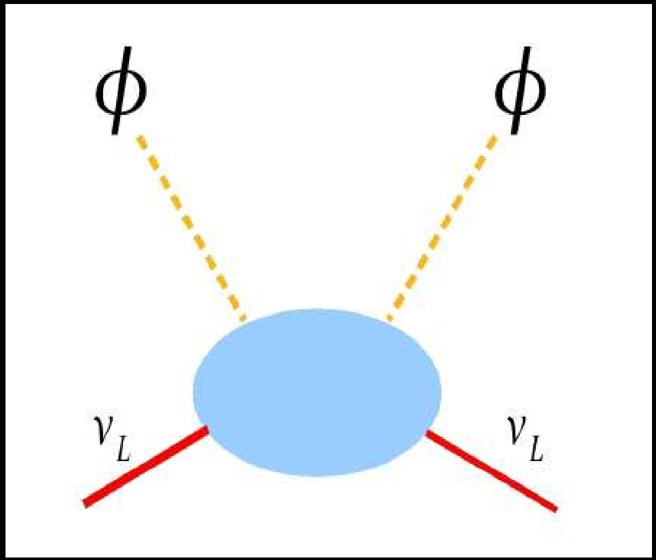
TYPE I

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

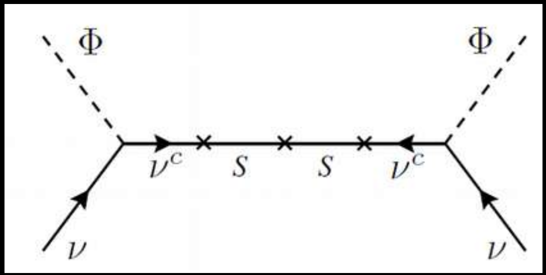
$$v_3 v_1 \sim {v_2}^2$$

coefficient
mechanism
scale
flavor structure

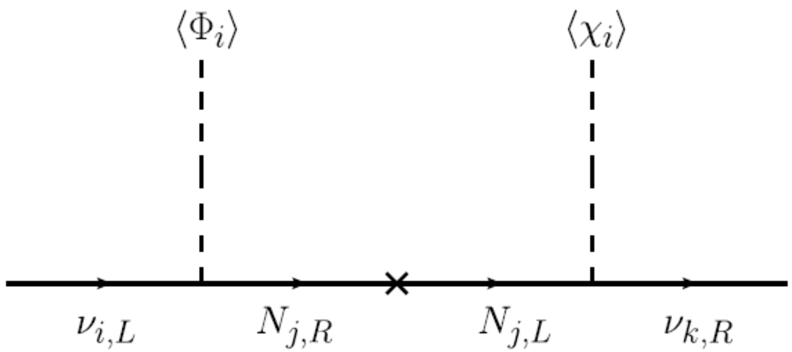
Arbitrary number of singlet messengers

LOW-SCALE SEESAW

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



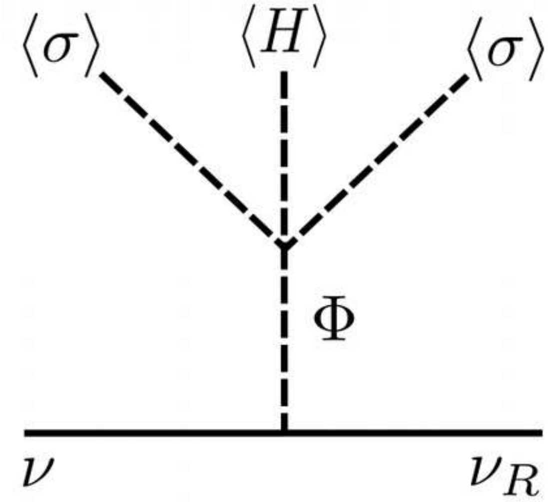
Seesawing a la Dirac



type1

Phys.Lett. B761 (2016) 431-436

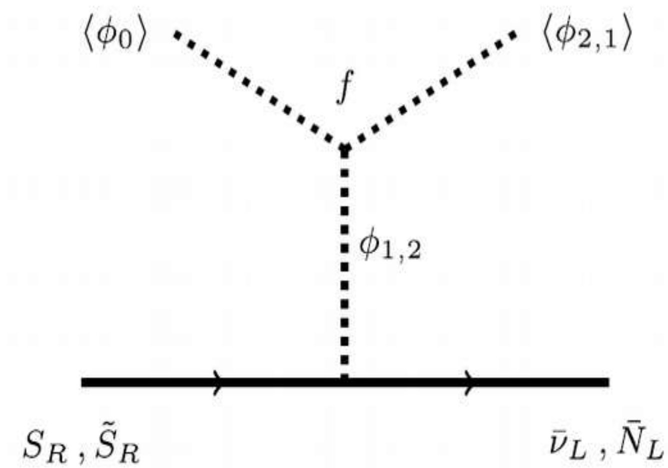
Phys.Lett. B767 (2017) 209-213



type2

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



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

Phys.Lett. B755 (2016) 363-366

symmetry protects small neutrino mass

Talks by
Srivastava & Centelles-Juliá

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

Radiative neutrino mass

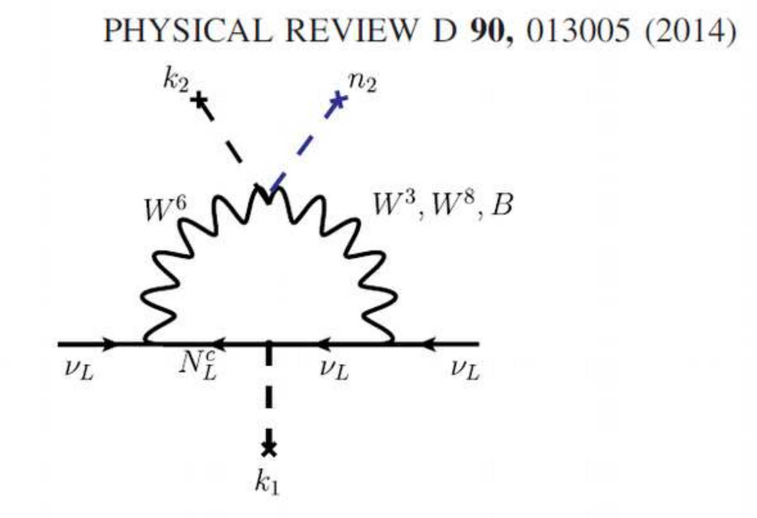
many low-scale neutrino mass schemes ...

arXiv:1404.3751

331 EW theory # families = # colours

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

Gauge vs Higgs



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

Radiative neutrino mass

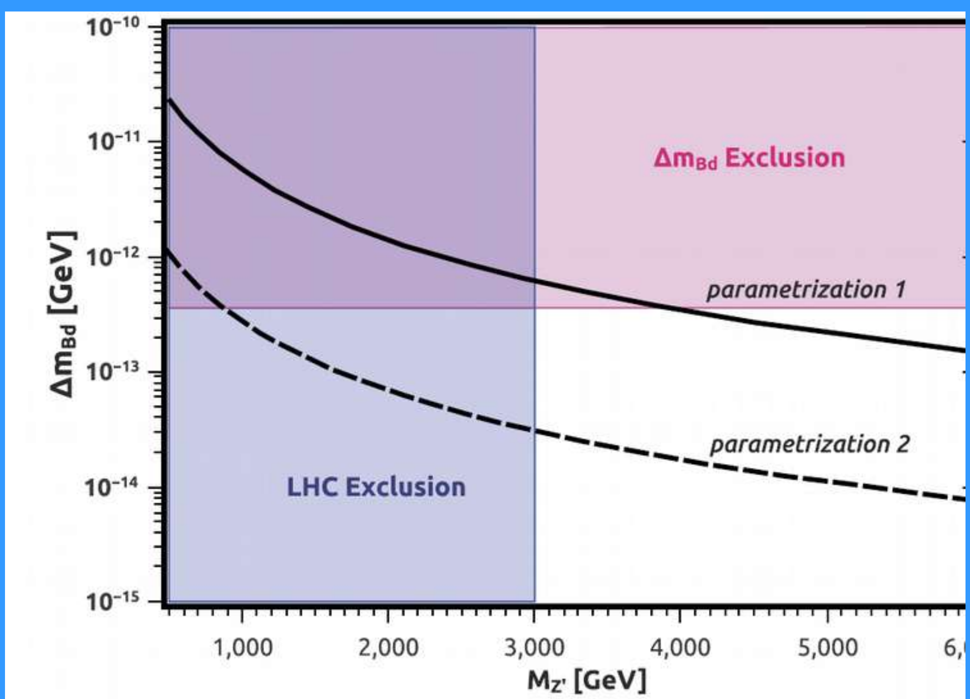
many low-scale neutrino mass schemes ...

arXiv:1404.3751

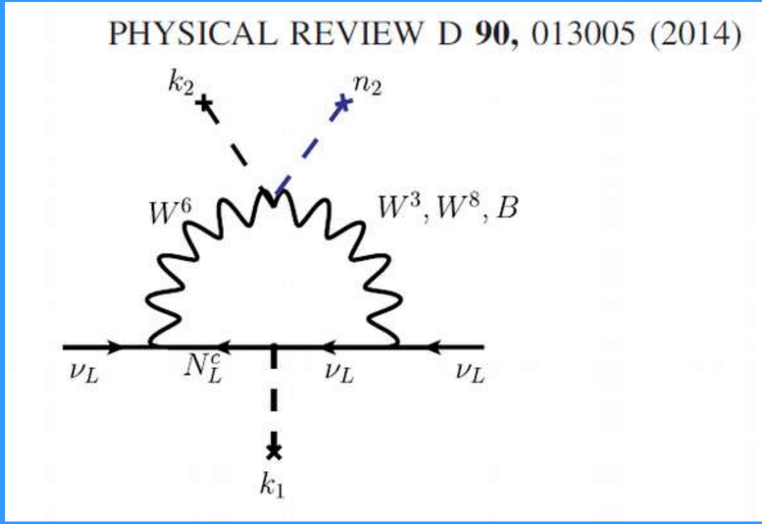
331 EW theory   # families = # colours

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

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

Simplest flavor symmetry

A4

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

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

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

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

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

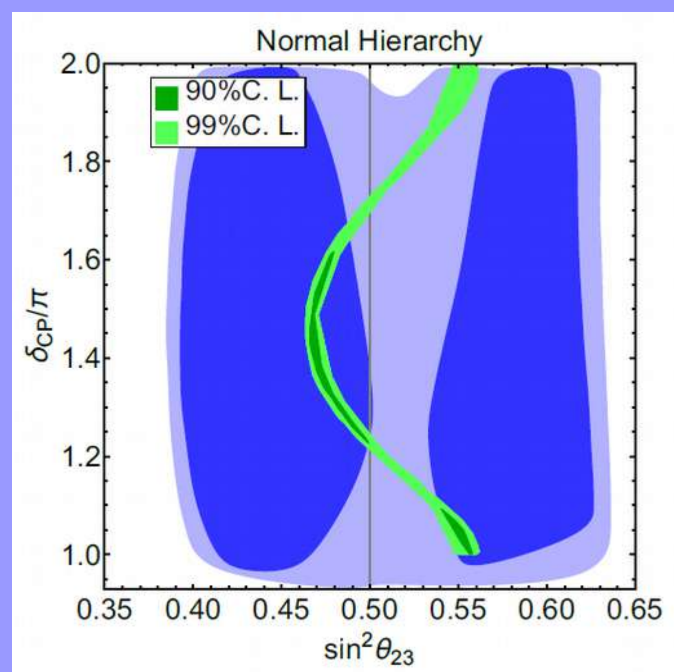
$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R$$

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

Revamping ...
Morisi et al, Phys.Rev. D88 (2013) 016003

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



prefers for NO
max CPV

BUT LO

will it survive DUNE?

family predictions from warped SM

:Chen et al JHEP01(2016)007

masses "explained" by geometry

angles related by symmetry

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

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

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

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

family predictions from warped SM

constrained global fitting

:Chen et al
JHEP01(2016)007

masses "explained" by geometry

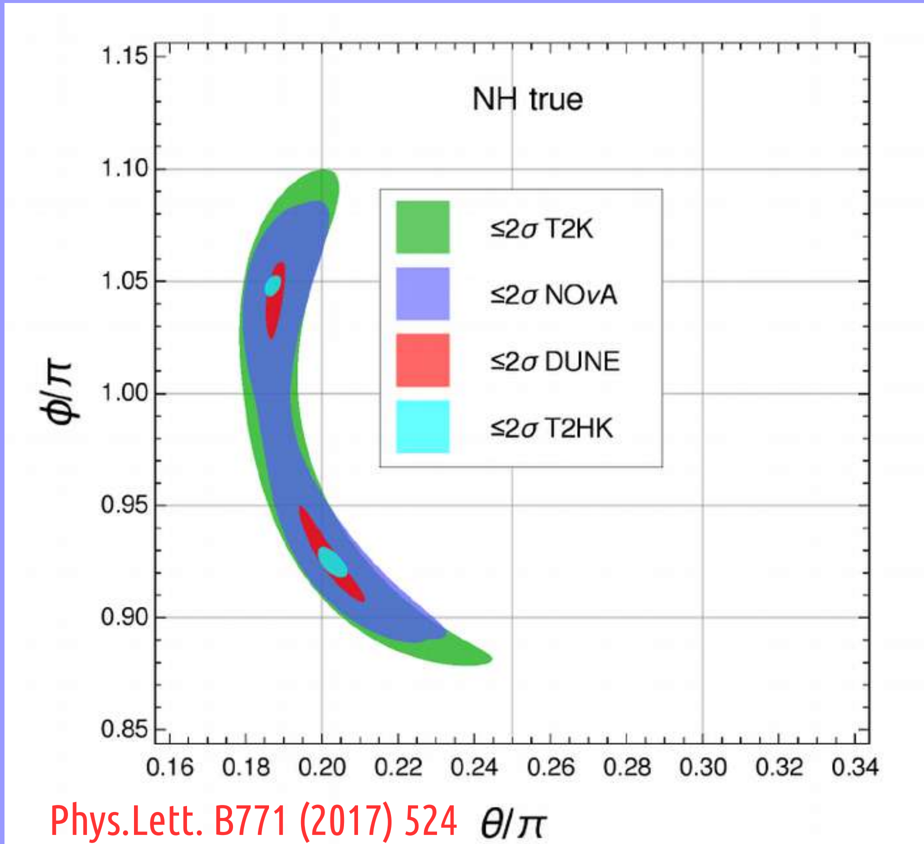
angles related by symmetry

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

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

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

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



Phys.Lett. B771 (2017) 524

Phys. Rev. D95 (2017) 095030

from oscillations to

charged fermion masses

Morisi et al Phys.Rev. D84 (2011) 036003

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

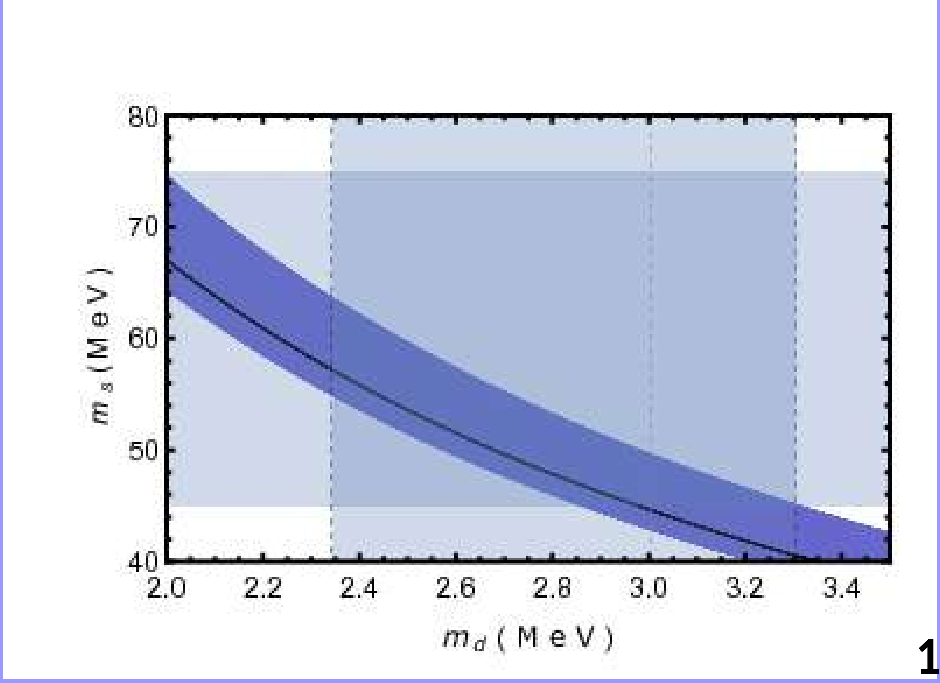
Morisi et al Phys.Rev. D88 (2013) 036001

Bonilla et al Phys.Lett. B742 (2015) 99

from oscillations to charged fermion masses

Golden Q-L unification

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



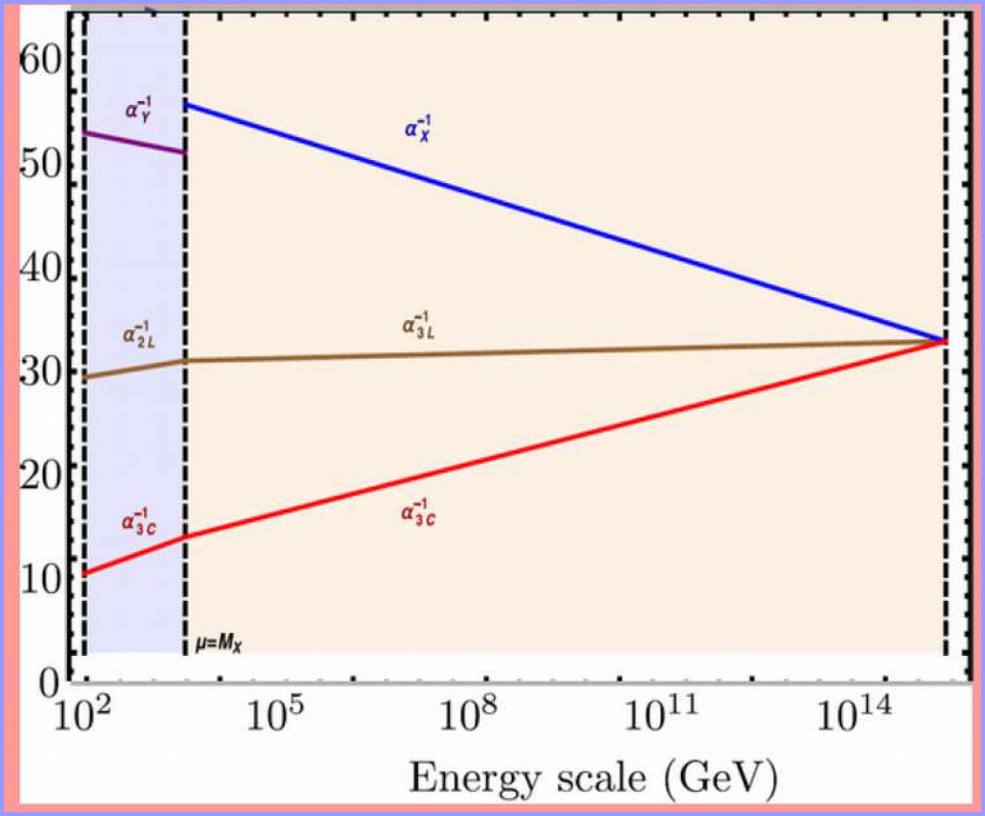
Morisi et al Phys.Rev. D84 (2011) 036003

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

neutrino masses as the cause of 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

Unifying forces & families

inspired by beauty of neutrinos in SO10

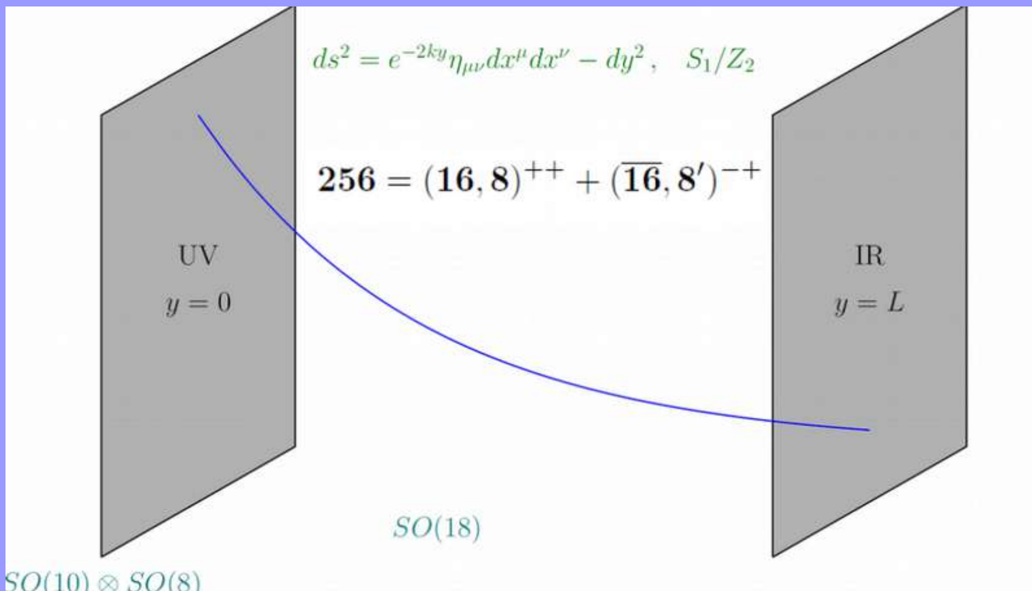
$$\mathbf{16} \rightarrow (\mathbf{3}, \mathbf{2}, 1/6) + (\mathbf{1}, \mathbf{2}, -1/2) + (\bar{\mathbf{3}}, \mathbf{1}, 1/3) + (\bar{\mathbf{3}}, \mathbf{1}, -2/3) + (\mathbf{1}, \mathbf{1}, 1) + (\mathbf{1}, \mathbf{1}, 0)\,,$$

Unifying forces & families

inspired by beauty of neutrinos in SO10

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

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



promote M4 to AdS5 & use
orbifold BC to decouple mirrors

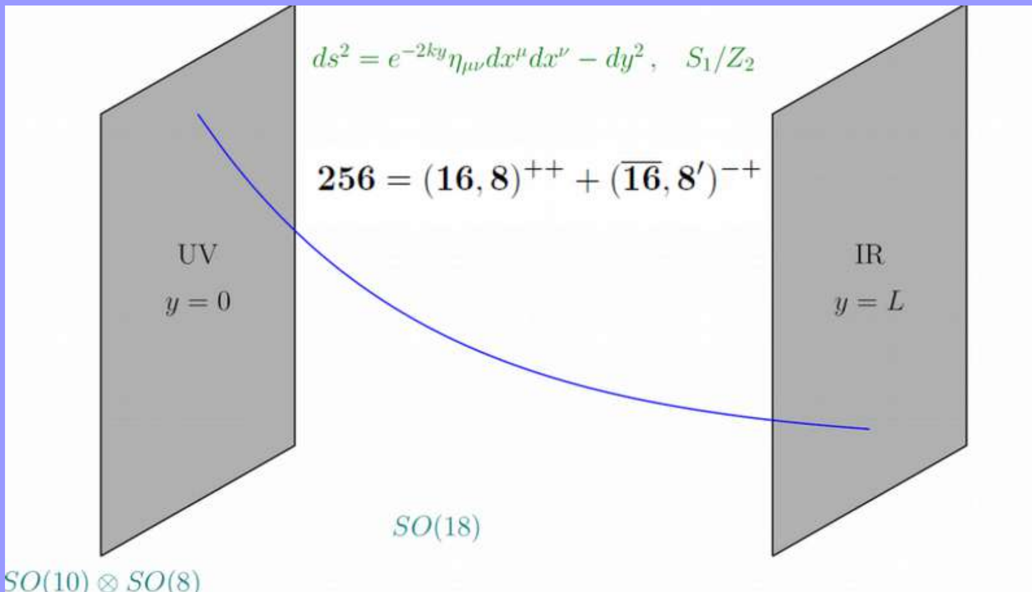
Unifying forces & families

inspired by beauty of neutrinos in SO10

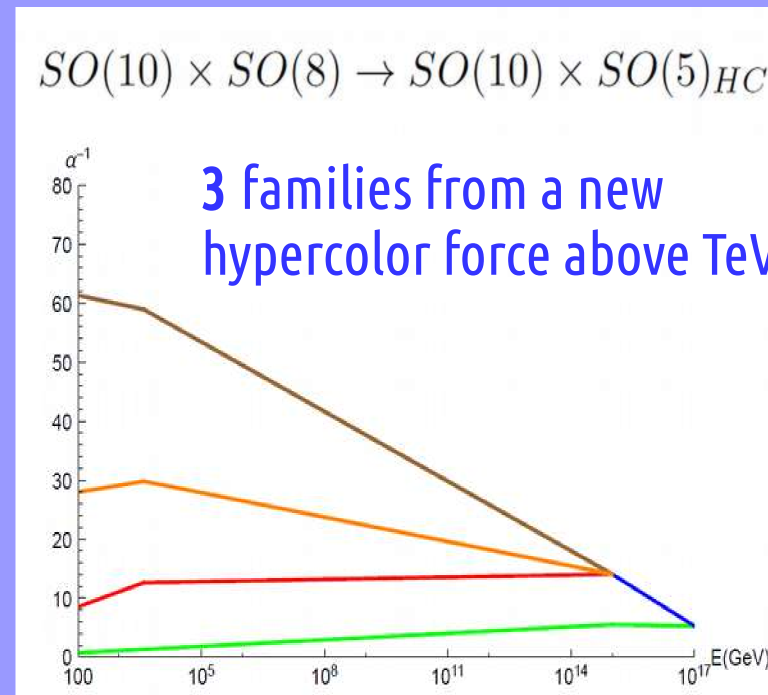
$$\mathbf{16} \to (\mathbf{3},\mathbf{2},1/6) + (\mathbf{1},\mathbf{2},-1/2) + (\bar{\mathbf{3}},\mathbf{1},1/3) + (\bar{\mathbf{3}},\mathbf{1},-2/3) + (\mathbf{1},\mathbf{1},1) + (\mathbf{1},\mathbf{1},0)\,,$$

Reig, Valle, Vaquera-Araujo, Wilczek

Phys.Lett. B774 (2017) 667-670



promote M4 to AdS5 & use orbifold BC to decouple mirrors



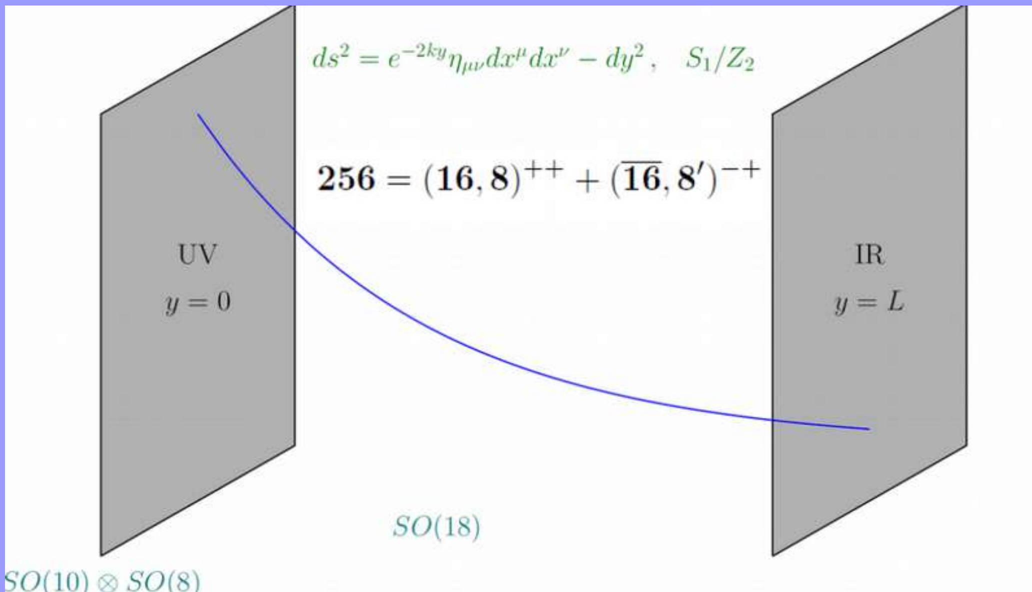
Unifying forces & families

inspired by beauty of neutrinos in SO10

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

Reig, Valle, Vaquera-Araujo, Wilczek

Phys.Lett. B774 (2017) 667-670



promote M4 to AdS5 & use orbifold BC to decouple mirrors

Reig, JV, Wilczek

http://arxiv.org/abs/arXiv:1805.08048

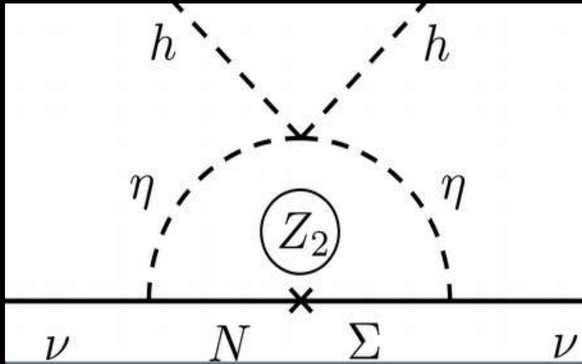
	q_L	u_R	d_R	l_L	e_R	ν_R	Φ^u	Φ^d	Ψ^u	Ψ^d	σ	ρ
$SU(3)_c$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**2**	**2**	**2**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	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 implies Golden Q-L unification

neutrino mass generation
may give the theory of DM

Talks by Peinado & Srivastava

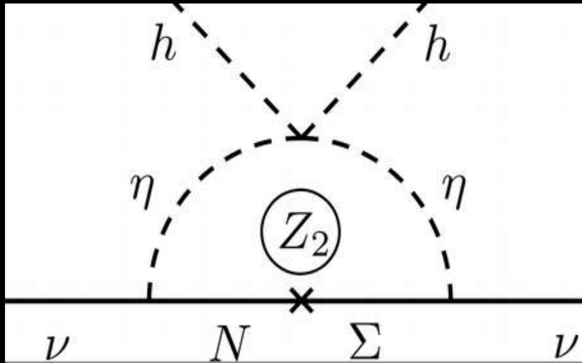


Scotogenic dark matter

	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
$\mathbb{Z}_2$	+	+	+	−	−	−	+

E Ma, Merle et al JHEP 1607 (2016) 013
Hirsch et al JHEP01(2016)007
Diaz et al http://dx.doi.org/10.1007/JHEP01(2016)007

DM as radiative neutrino mass messenger



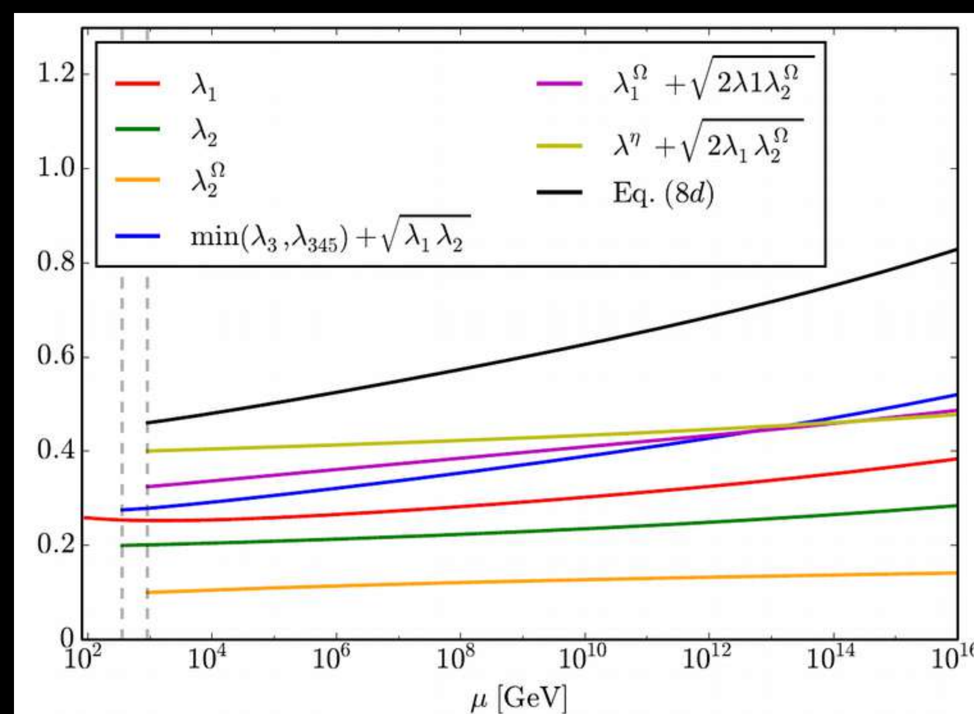
Scotogenic dark matter

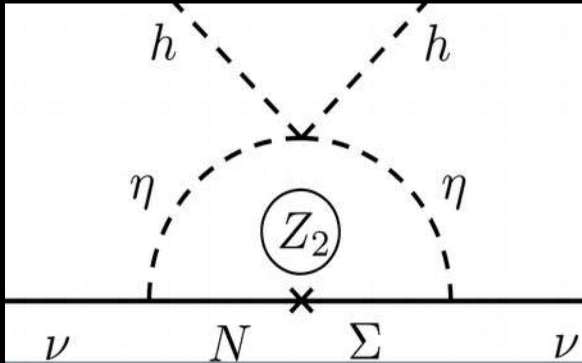
	Standard Model			Fermions		Scalars	
	L	e	ϕ	Σ	N	η	Ω
Generations	3	3	1	1	1	1	1
$SU(2)_L$	2	1	2	3	1	2	3
$U(1)_Y$	-1/2	-1	1/2	0	0	1/2	0
$\mathbb{Z}_2$	+	+	+	−	−	−	+

E Ma, Merle et al JHEP 1607 (2016) 013
Hirsch et al JHEP01(2016)007
Diaz et al http://dx.doi.org/10.1007/JHEP01(2016)007

DM as radiative neutrino mass messenger

rge running preservation of Z2





Scotogenic dark matter

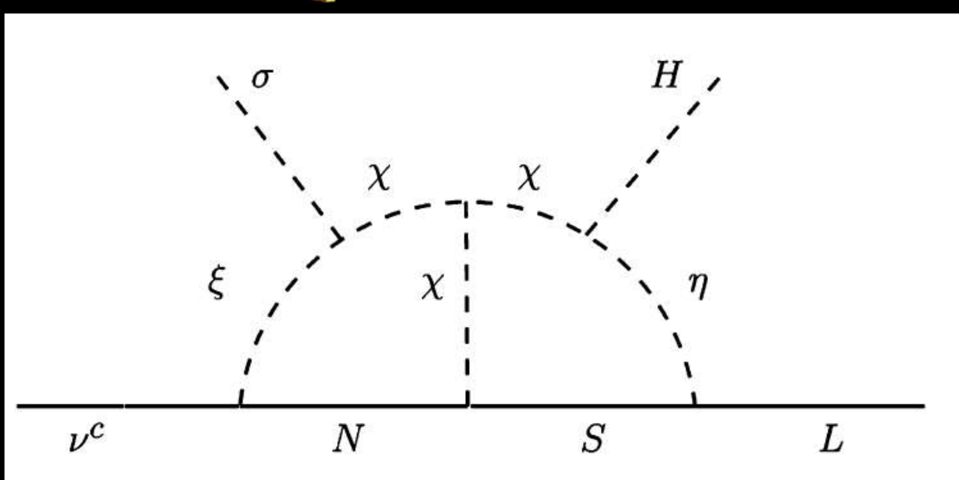
	Standard Model			Fermions		Scalars	
	L	e	ϕ	Σ	N	η	Ω
Generations	3	3	1	1	1	1	1
$SU(2)_L$	2	1	2	3	1	2	3
$U(1)_Y$	-1/2	-1	1/2	0	0	1/2	0
$\mathbb{Z}_2$	+	+	+	−	−	−	+

E Ma, Merle et al JHEP 1607 (2016) 013
Hirsch et al JHEP01(2016)007
Diaz et al http://dx.doi.org/10.1007/JHEP01(2016)007

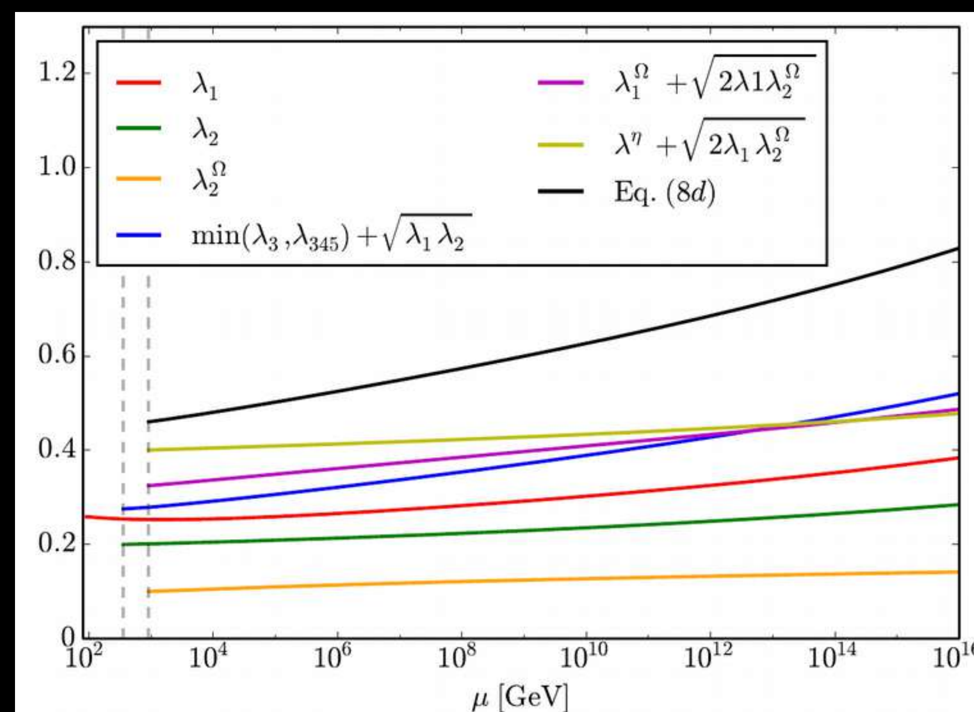
DM as radiative neutrino mass messenger

rge running preservation of Z2

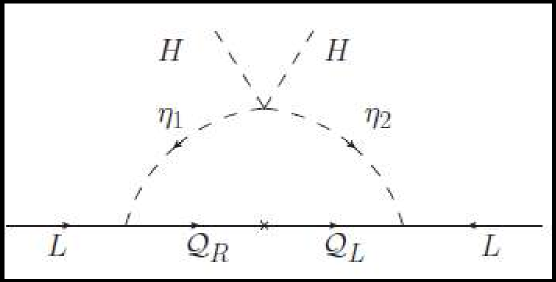
2-loop dirac variant



http://dx.doi.org/10.1016/j.physletb.2016.09.027

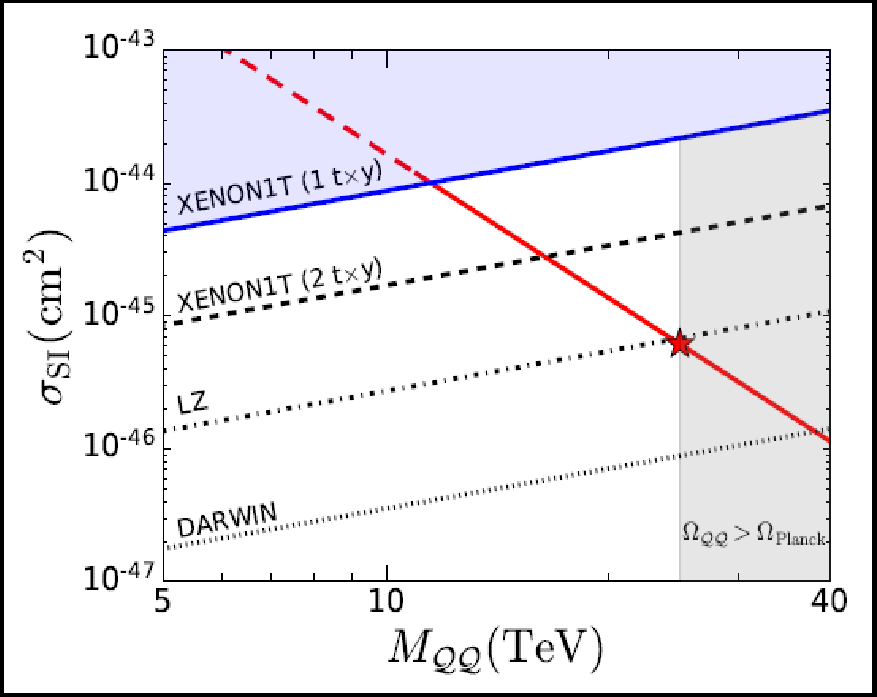


bound-state dark matter & neutrinos



Particles	$\mathrm{U}(1)_D$	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
$Q_i = \begin{pmatrix} u_L & d_L \end{pmatrix}^T_i$	0	$(\mathbf{3},\mathbf{2})_{1/6}$
$\overline{u_{Ri}}$	0	$(\bar{\mathbf{3}},\mathbf{1})_{-2/3}$
$\overline{d_{Ri}}$	0	$(\bar{\mathbf{3}},\mathbf{1})_{1/3}$
$L_i = \begin{pmatrix} \nu_L & e_L \end{pmatrix}^T_i$	0	$(\mathbf{1},\mathbf{2})_{-1/2}$
$\overline{e_{Ri}}$	0	$(\mathbf{1},\mathbf{1})_1$
Q_L	-1	$(\mathbf{N}_c,\mathbf{1})_0$
$\overline{Q_R}$	1	$(\mathbf{N}_c,\mathbf{1})_0$
H	0	$(\mathbf{1},\mathbf{2})_{1/2}$
η_a	$(-1)^a$	$(\mathbf{N}_c,\mathbf{2})_{1/2}$

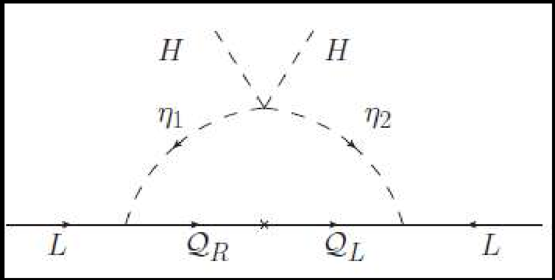
DM stable due to assumed U(1)_D



DM constituent as radiative messenger

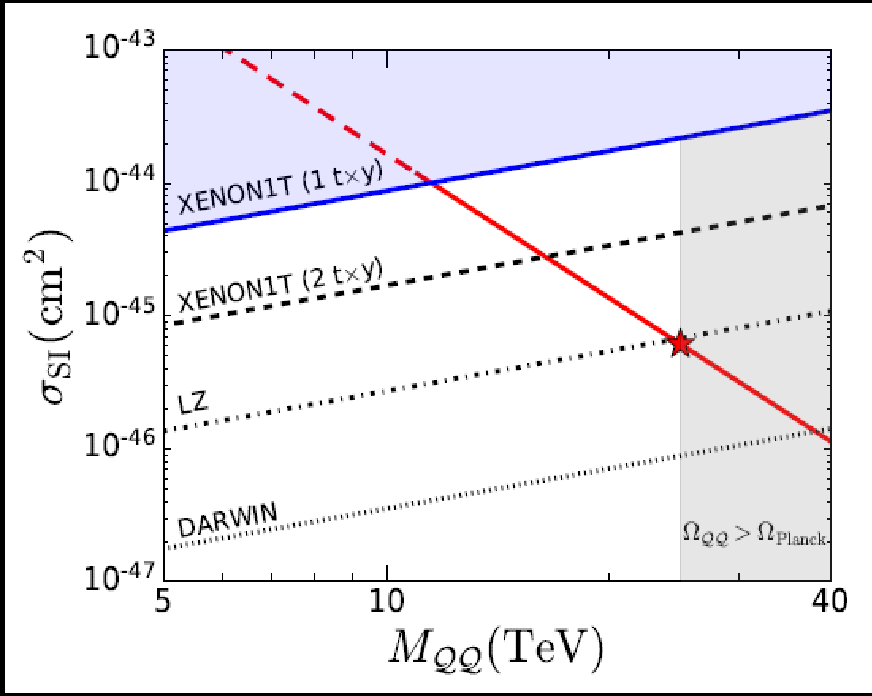
http://arxiv.org/abs/arXiv:1806.09977

bound-state dark matter & neutrinos



Particles	$U(1)_D$	$(SU(3)_c, SU(2)_L)_Y$
$Q_i = \begin{pmatrix} u_L & d_L \end{pmatrix}^T_i$	0	$(\mathbf{3},\mathbf{2})_{1/6}$
$\overline{u_{Ri}}$	0	$(\bar{\mathbf{3}},\mathbf{1})_{-2/3}$
$\overline{d_{Ri}}$	0	$(\bar{\mathbf{3}},\mathbf{1})_{1/3}$
$L_i = \begin{pmatrix} \nu_L & e_L \end{pmatrix}^T_i$	0	$(\mathbf{1},\mathbf{2})_{-1/2}$
$\overline{e_{Ri}}$	0	$(\mathbf{1},\mathbf{1})_1$
Q_L	-1	$(\mathbf{N}_c,\mathbf{1})_0$
$\overline{Q_R}$	1	$(\mathbf{N}_c,\mathbf{1})_0$
H	0	$(\mathbf{1},\mathbf{2})_{1/2}$
η_a	$(-1)^a$	$(\mathbf{N}_c,\mathbf{2})_{1/2}$

DM stable due to assumed U(1)_D



DM constituent as radiative messenger

http://arxiv.org/abs/arXiv:1806.09977

DM stability from Diracness

https://doi.org/10.1103/PhysRevD.97.115032

DM sable because neutrinos are Dirac **U(1)_D = U(1)_L**

some take home tasks:

- further flavor model building: more flasys
- incorporate DM, in well-motivated way e.g. schemes with DM stability from gauge matter parity

Alves et al Phys.Lett. B772 (2017) 825–831

get cosmology as emergent theory

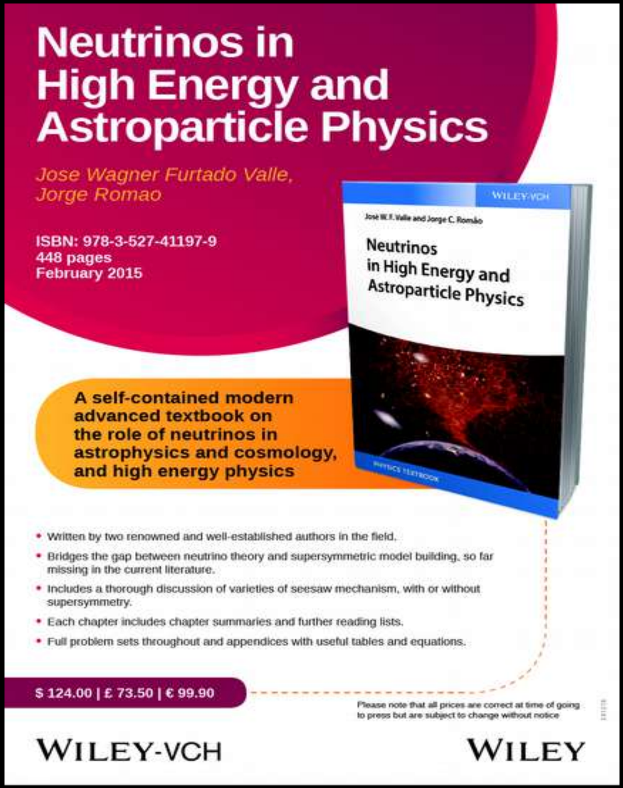
Some ideas/hints

Majoron as DM + inflaton
https://doi.org/10.1103/PhysRevD.90.055023

Asymmetric Dark Matter, Inflation and Leptogenesis from B-L Symmetry Breaking arXiv:1805.08251

Smoot arXiv:1405.2776 also Dark Energy?

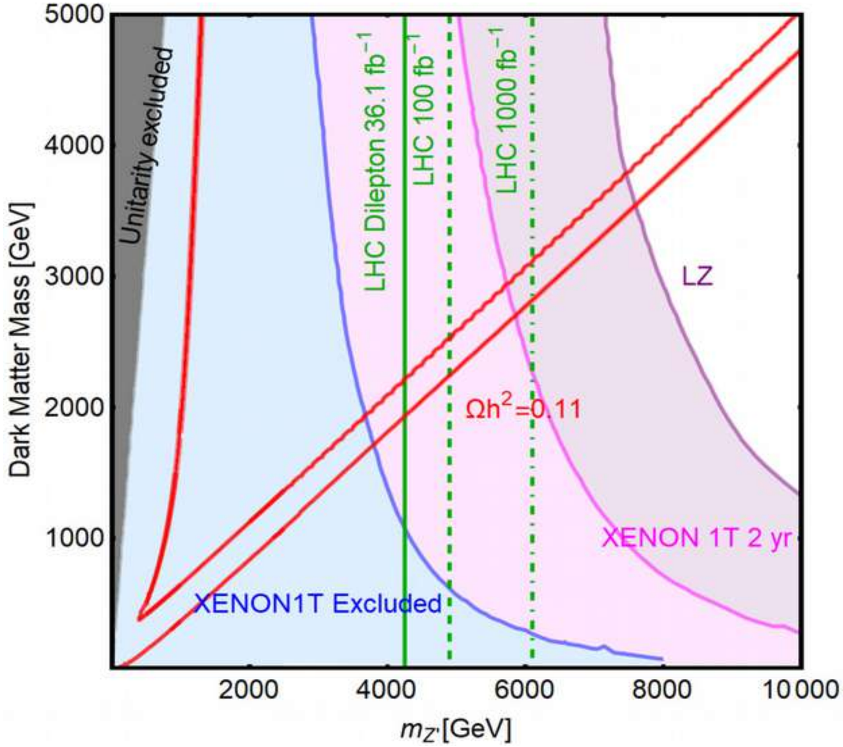
Back-ups


Neutrinos in
High Energy and
Astroparticle Physics
Jose Wagner Furtado Valle,
Jorge Romao
ISBN: 978-3-527-41197-9
448 pages
February 2015
WILEY-VCH
Neutrinos
in High Energy and
Astroparticle Physics
A self-contained modern
advanced textbook on
the role of neutrinos in
astrophysics and cosmology,
and high energy physics
• Written by two renowned and well-established authors in the field.
• Bridges the gap between neutrino theory and supersymmetric model building, so far missing in the current literature.
• Includes a thorough discussion of varieties of seesaw mechanism, with or without supersymmetry.
• Each chapter includes chapter summaries and further reading lists.
• Full problem sets throughout and appendices with useful tables and equations.
$ 124.00 | £ 73.50 | € 99.90
Please note that all prices are correct at time of going to press but are subject to change without notice
WILEY-VCH
WILEY

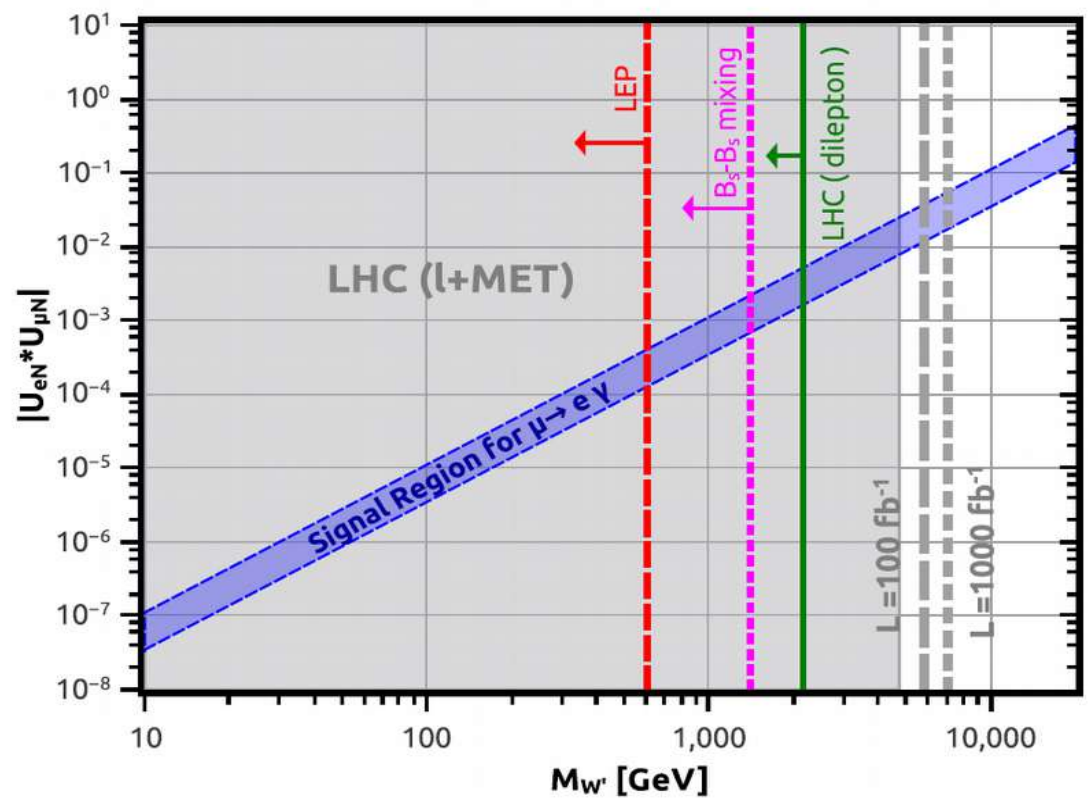
DM stability from gauge matter parity

Alves et al

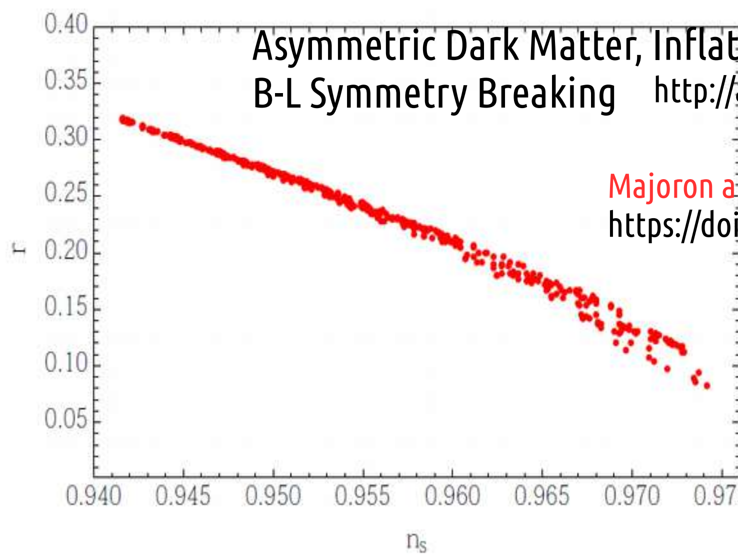
Phys.Lett. B772 (2017) 825–831



Matter-parity as a residual gauge symmetry: Probing a theory of cosmological dark matter 3-3-1-1 EW extension



cosmology from seesaw



Asymmetric Dark Matter, Inflation and Leptogenesis from B-L Symmetry Breaking http://arxiv.org/abs/arXiv:1805.08251

Majoron alternative

https://doi.org/10.1103/PhysRevD.90.055023

status of neutrino oscillations 2018

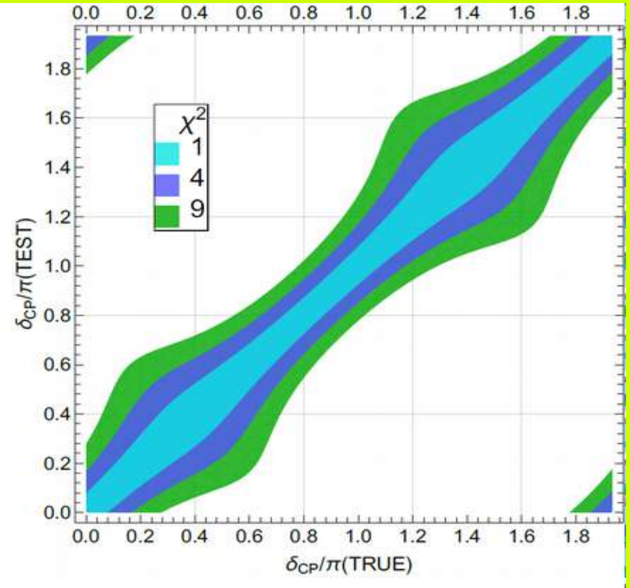
the numbers

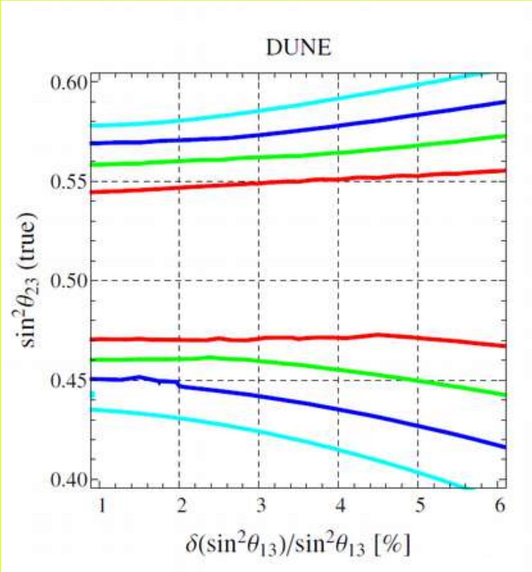
Neutrino oscillation parameters summary determined from this global analysis. The ranges for inverted ordering refer to the local minimum for this neutrino mass ordering.

Parameter	Best fit $\pm$ 1σ	2σ range	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NO)	2.50±0.03	2.44–2.57	2.41–2.60
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (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
$\theta_{12}/°$	$34.5^{+1.2}_{-1.0}$	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
$\theta_{23}/°$	$47.7^{+1.2}_{-1.7}$	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
$\theta_{23}/°$	$47.9^{+1.0}_{-1.7}$	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
$\theta_{13}/°$	$8.45^{+0.16}_{-0.14}$	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
$\theta_{13}/°$	$8.53^{+0.14}_{-0.15}$	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
$\delta/°$	238^{+38}_{-27}	182–315	157–349
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94
$\delta/°$	281^{+23}_{-27}	229–328	202–349

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

the future





10.1016/j.physletb.2017.05.080

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.96.011303

robustness

Miranda & JV, Nucl.Phys. B908 (2016) 436
Escrihuela, et al PhysRevD.92.053009
Miranda et al, PhysRevLett.117.061804

non unitarity

CP confusion

new ways to probe seesaw scale

http://dx.doi.org/10.1103/PhysRevD.95.033005

http://arxiv.org/abs/arXiv:1612.07377

new window into BSM physics e.g. nsi

Coloma, Huber et al, Miranda et al,
de Gouvea et al, Goswami et al, Kopp et el
Antusch et al, many others ...

Are the B decay anomalies related to neutrino oscillations?

Sofiane M. Boucenna [a], José W.F. Valle [b], Avelino Vicente [b,c,*]

Phys.Lett. B750 (2015) 367-371

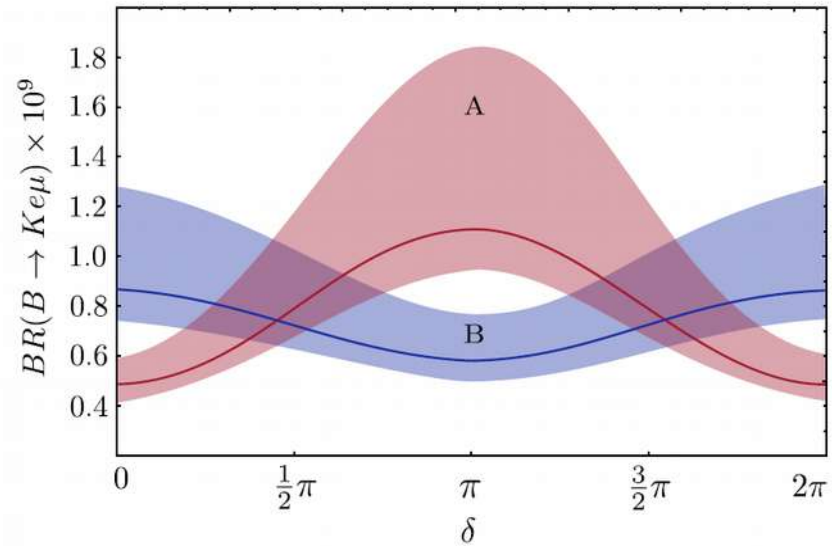


Fig. 1. The branching ratio of the decay $B \to Ke\mu$ versus the CP violating phase δ in scenarios A and B. The bands are obtained by taking the leptonic mixing angles within their 1σ range w.r.t. the best-fit value (solid line) [26].