neutrinos as gate to new physics

José W F Valle

IFIC

ASTROPARTICLES
Astroparticles and High Energy Physics Group

CSIC
Consejo Superior de Investigaciones Científicas

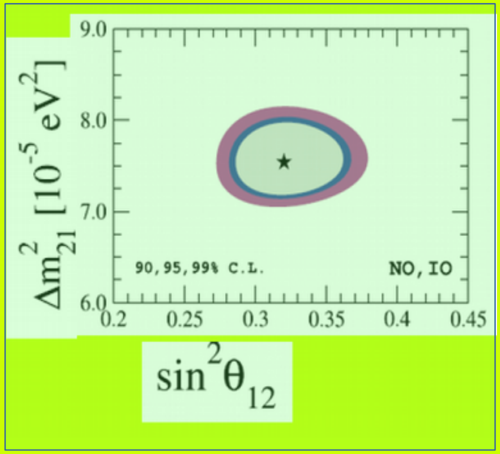
Vniversitat de València

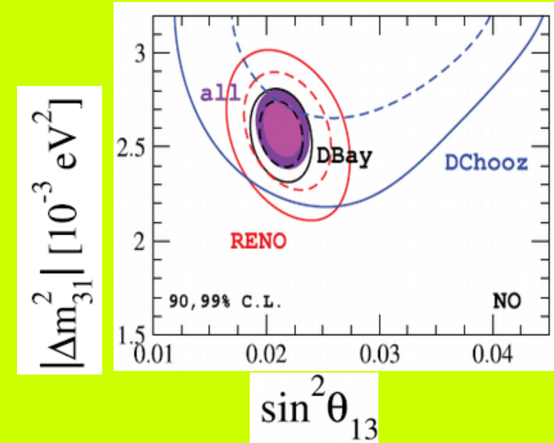
Excelencia Severo Ochoa

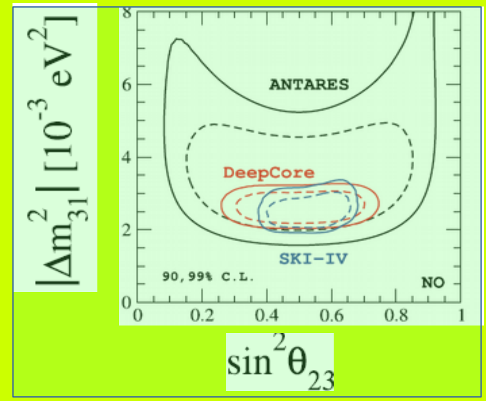
FLASY 2019

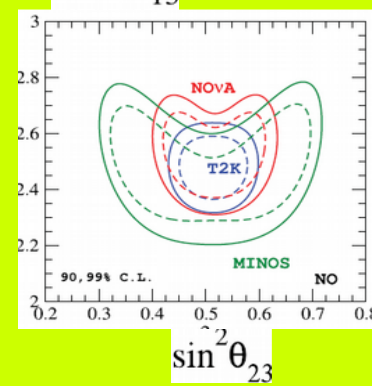
Hefei, China (July 2019)

status of neutrino oscillations



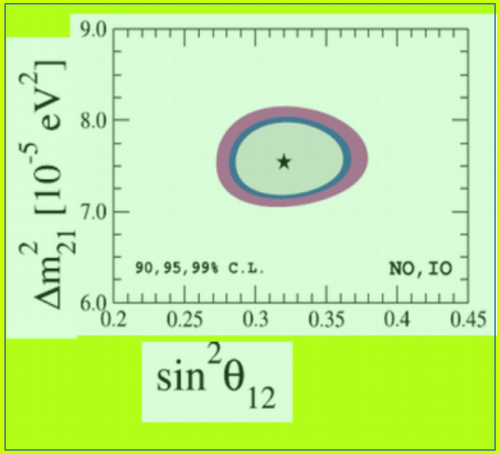


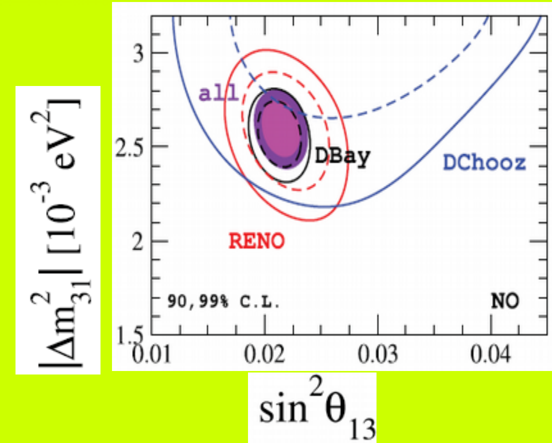


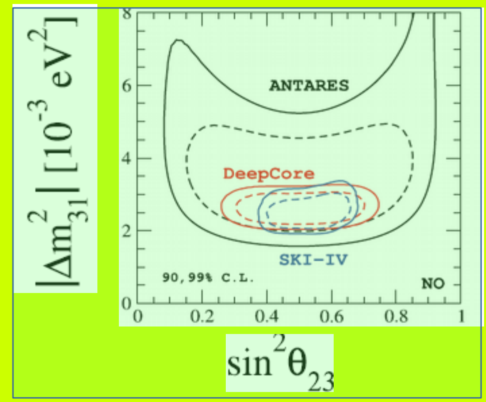


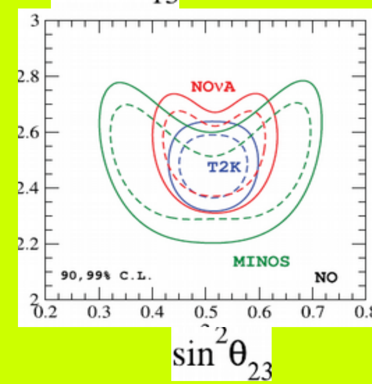
P.F. de Salas et al, PLB782 (2018) 633
https://globalfit.astroparticles.es/

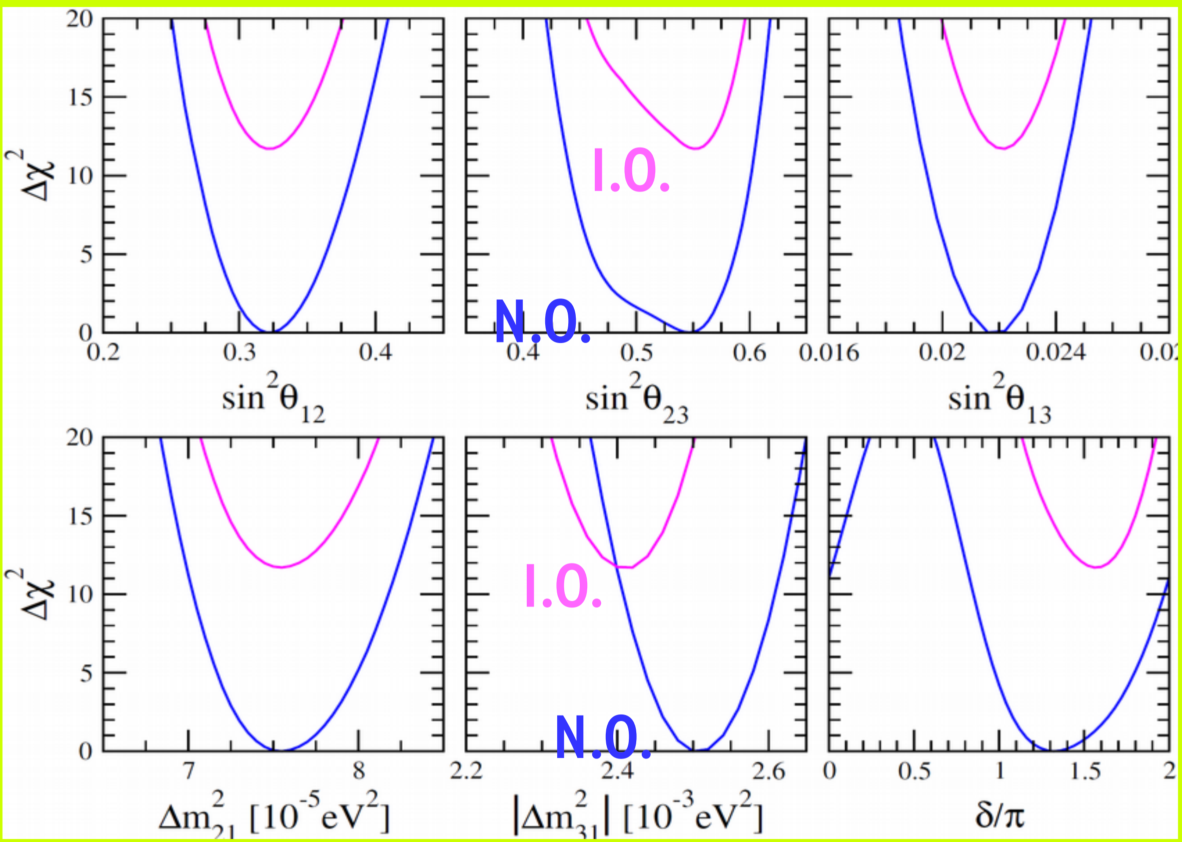
status of neutrino oscillations









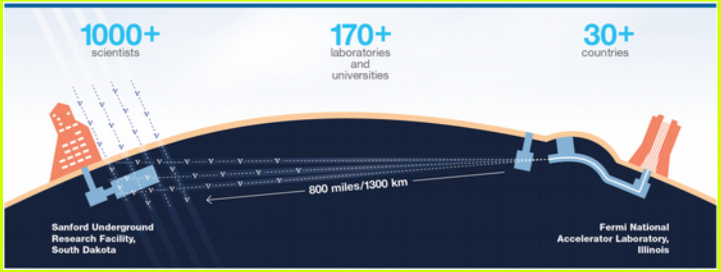


P.F. de Salas et al, PLB782 (2018) 633
https://globalfit.astroparticles.es/

Consistent global picture
Good agreement amongst groups

mass ordering : normal @ >3σ

leptonic CP violation



- CP phase
- atm octant

P.F. de Salas et al, PLB782 (2018) 633

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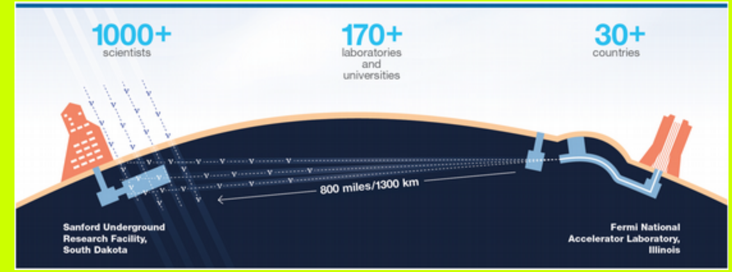


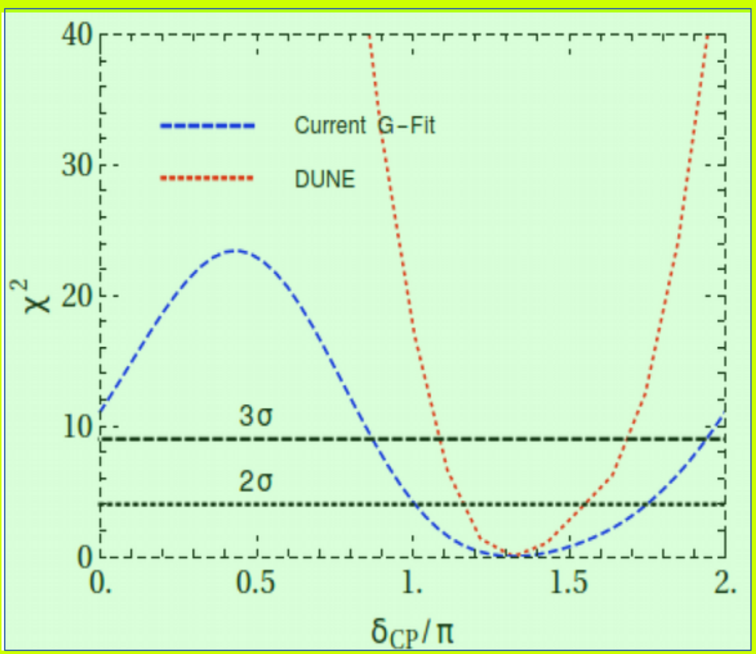
P.F. de Salas et al, PLB782 (2018) 633

https://globalfit.astroparticles.es/

improve at the next generation experiments

CP phase

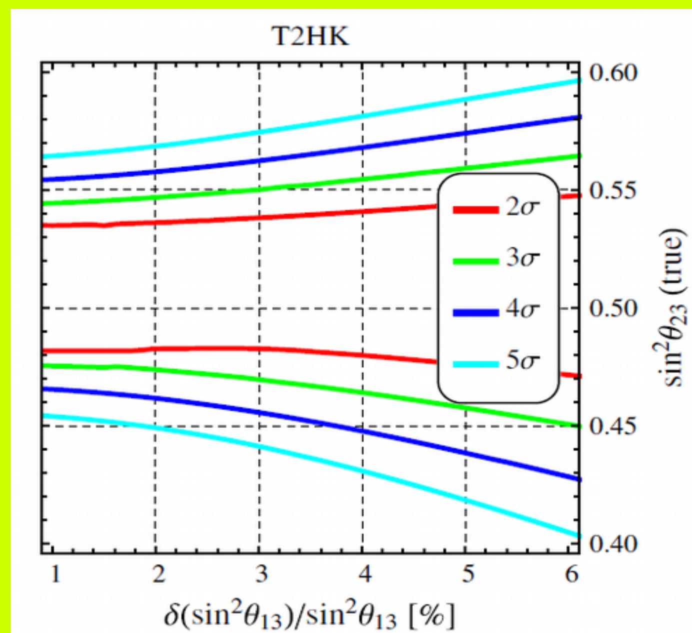
from
1811.07040



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

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

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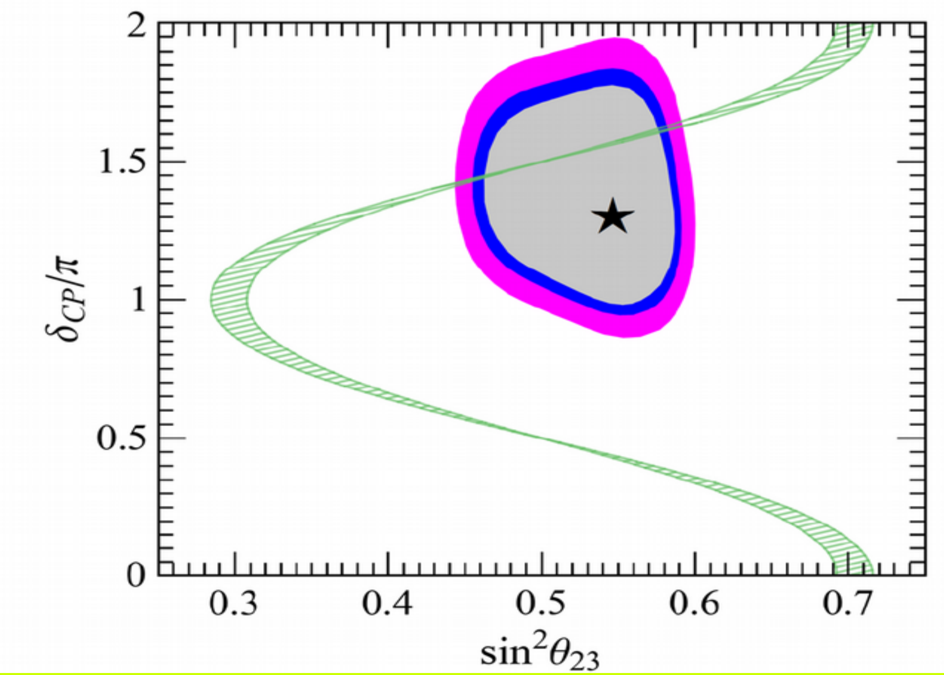

from Phys.Rev. D98 (2018) 055019

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Bi-Large lepton mixing pattern

from 1904.05632

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

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

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
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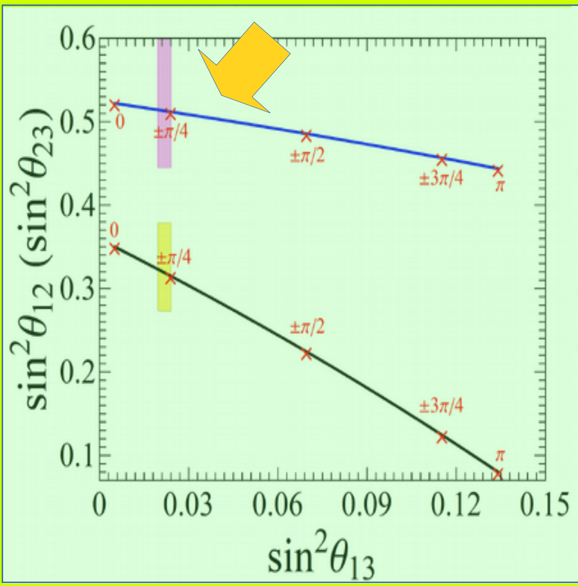

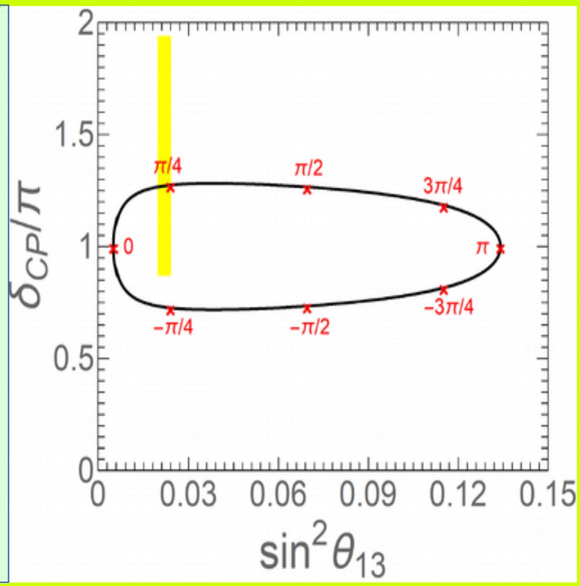

predicting solar, atm & CP from reactor angle

also 2-parameter generalizations of Bi-Large mixing

Bi-Large lepton mixing pattern

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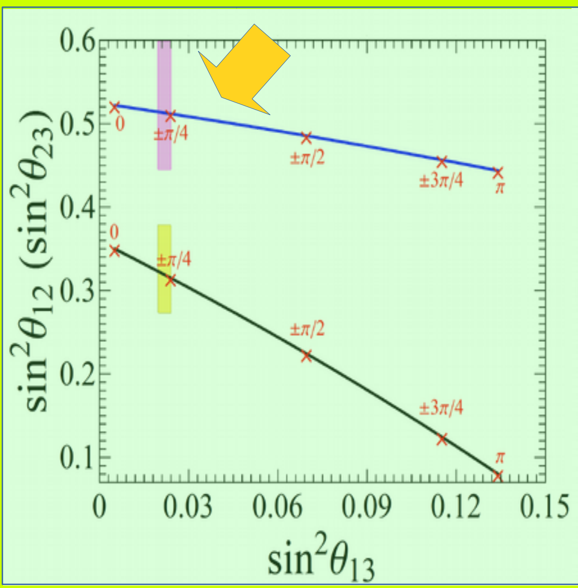

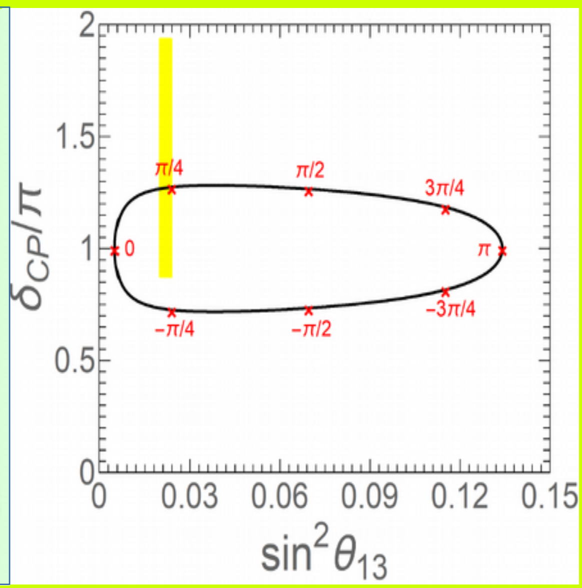

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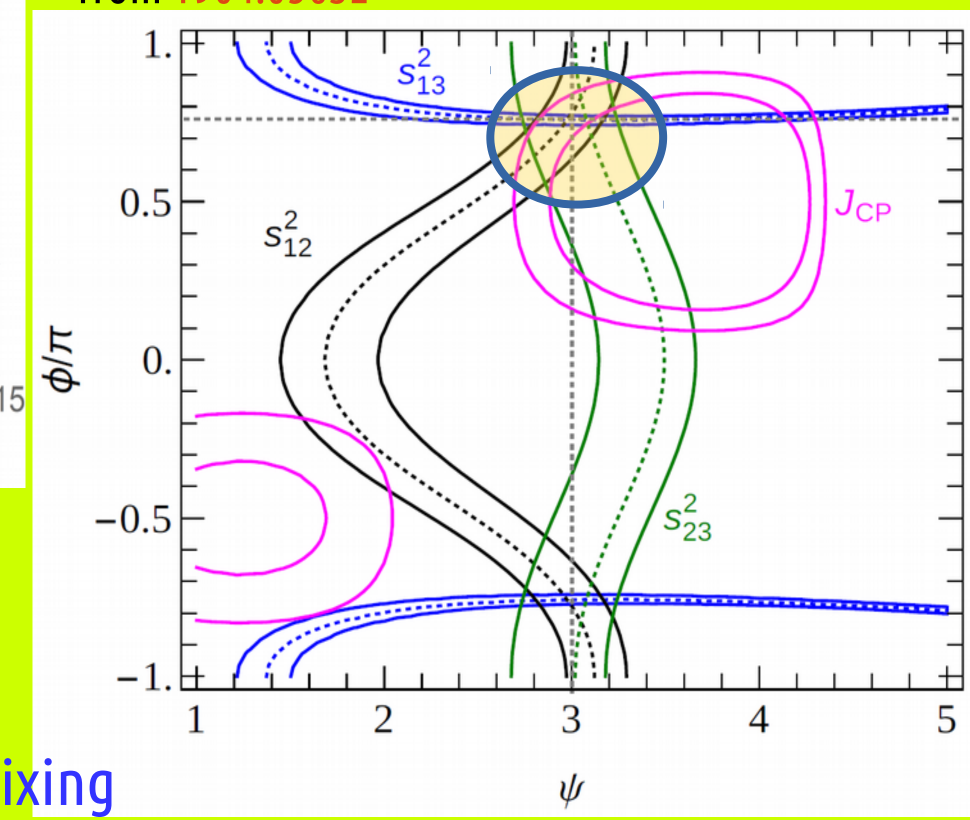

predicting solar, atm & CP from reactor angle

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

robustness

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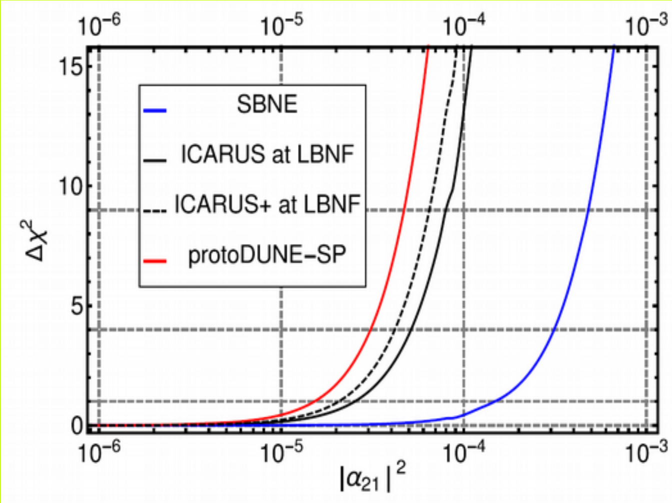
unitarity test as seesaw scale probe

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}
$\|\alpha_{32}\|<$	9.8×10^{-3}	1.7×10^{-2}	1.6×10^{-2}	2.1×10^{-2}

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 ...

robustness

J.V. Phys.Lett. B199 (1987) 432-436
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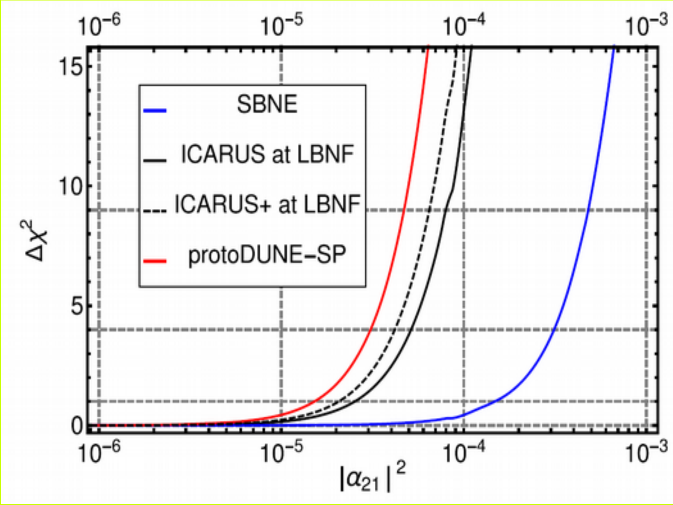
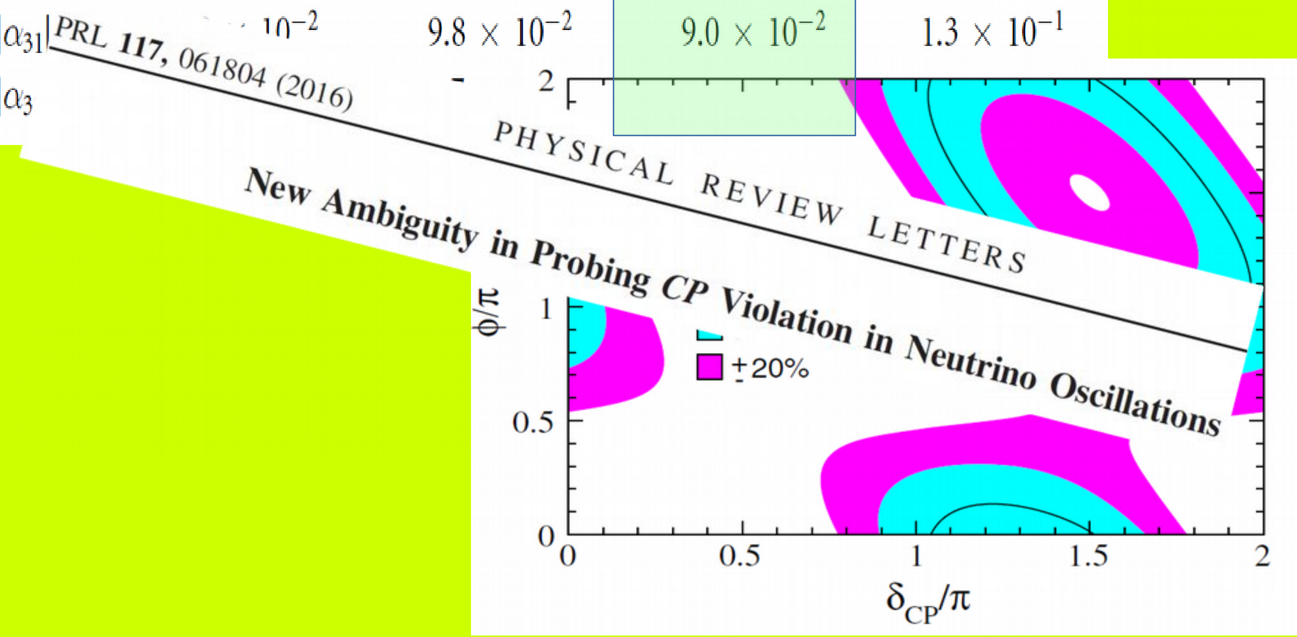
$\|\alpha_{3}$ [illegible]	[illegible]	[illegible]	[illegible]	[illegible]

window to BSM physics

PRD97 (2018) 095026

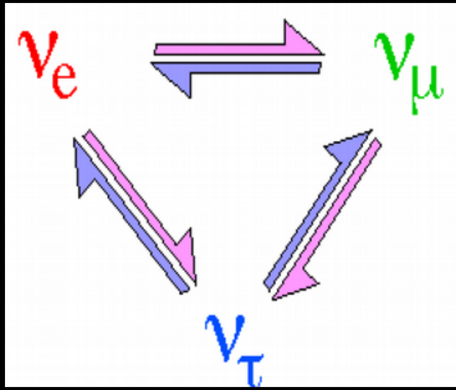




nsi Coloma, Huber et al, Miranda et al, de Gouvea et al, Goswami et al, Kopp et el, Antusch et al, Fernandez, Lopez Pavon, et al ...

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

new physics at last!!



Oscillations bring neutrinos to the center of the stage

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

e.g. flavor, EW breaking, unification, DM …

ABSOLUTE MASS & MAJORANA PHASES

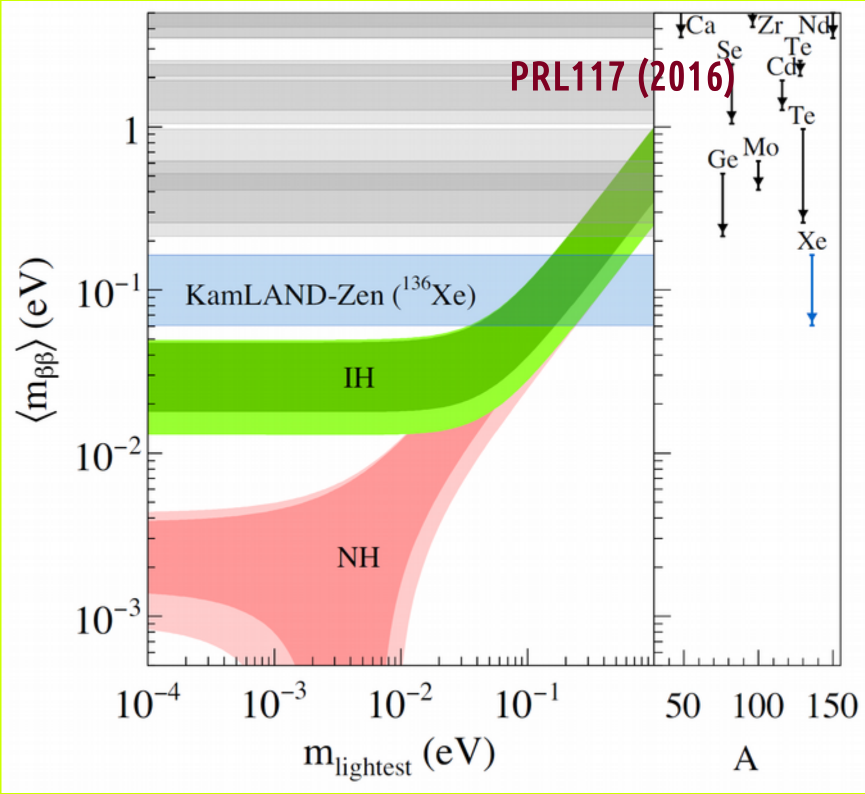
neutrinoless doublebeta decay

symmetric parametrization of lepton mixing matrix

Schechter & JV PRD22 (1980) 2227

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

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



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

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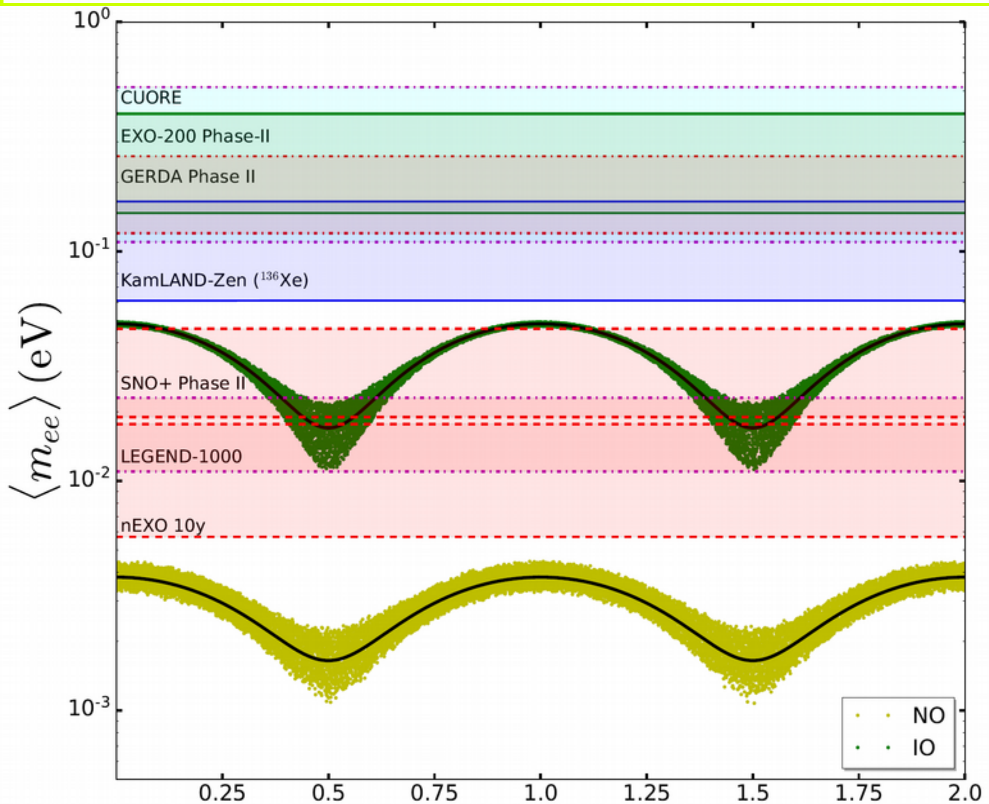
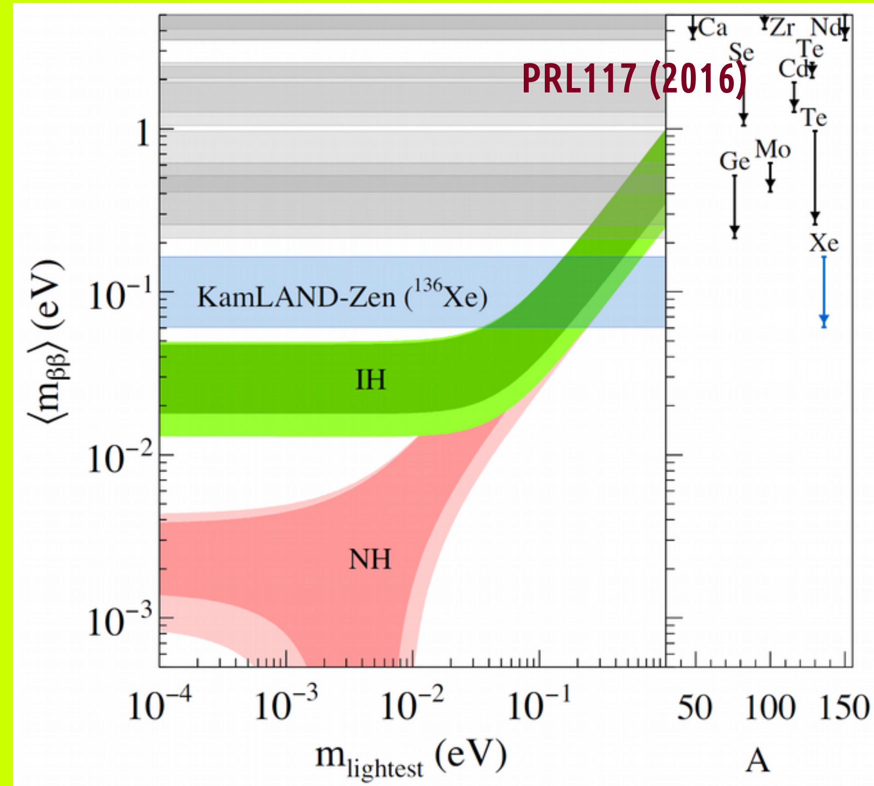


Majorana phase



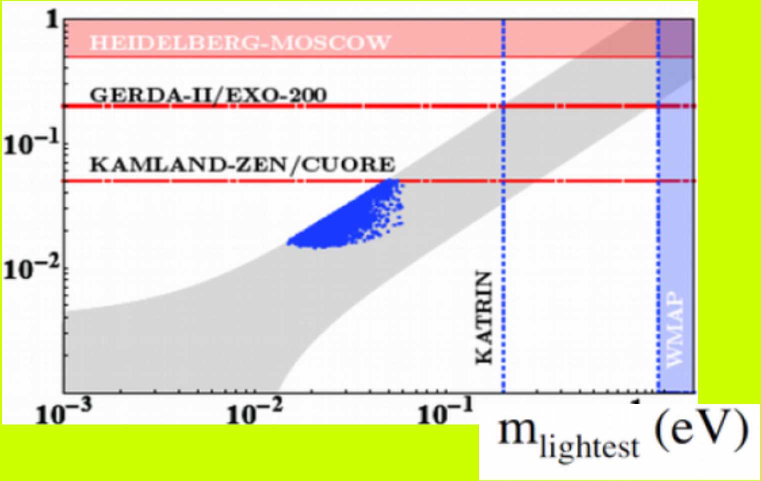
nEXO, **CUORE** , LEGEND (nGERDA/Majorana) ...

if one neutrino is massless

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

neutrinoless doublebeta decay

flavor sensitivity



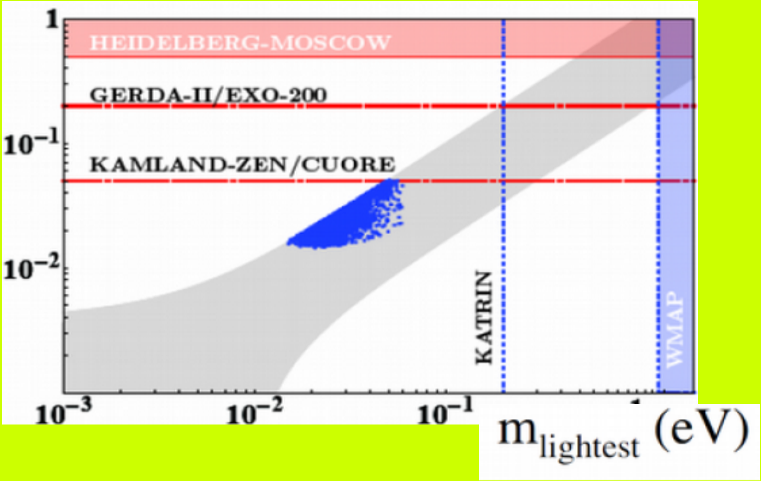
lower bounds even for normal ordering

Dorame et al
NPB861 (2012) 259-270

Dorame et al
PhysRevD.86.056001

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

neutrinoless doublebeta decay



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Dorame et al
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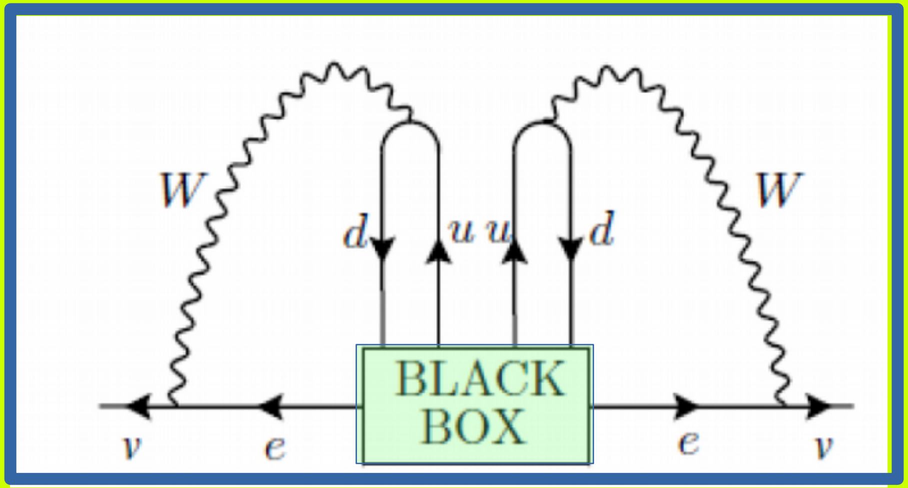
PhysRevD.86.056001

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

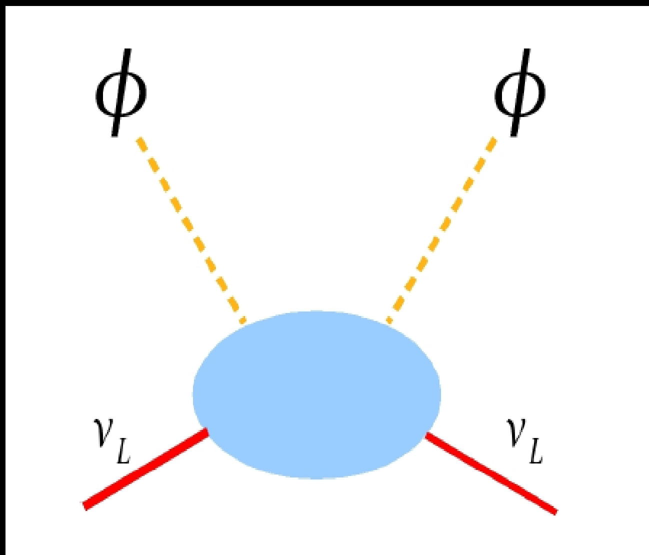
significance

Schechter, Valle 82

Lindner et al JHEP 1106 (2011) 091



Origin of neutrino mass

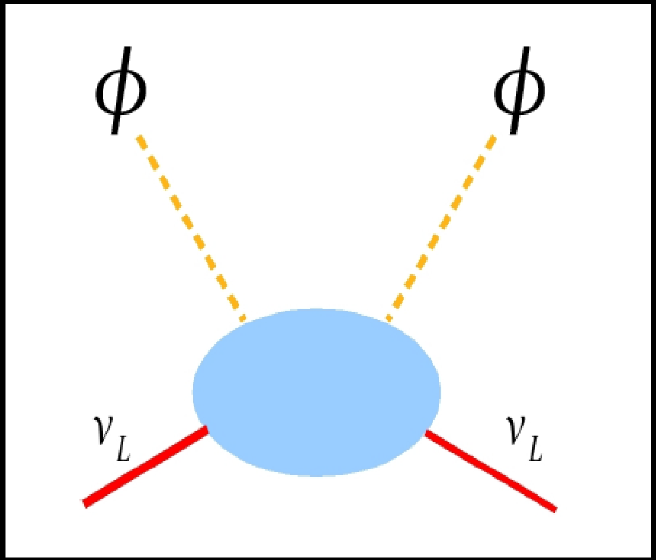


seesaw

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

coefficient
mechanism
scale
flavor structure

Origin of neutrino mass



coefficient
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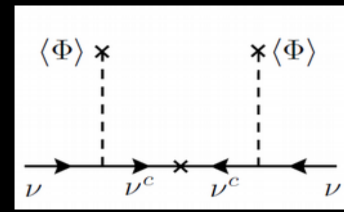
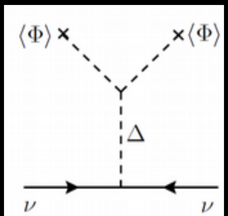


TYPE I

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

seesaw

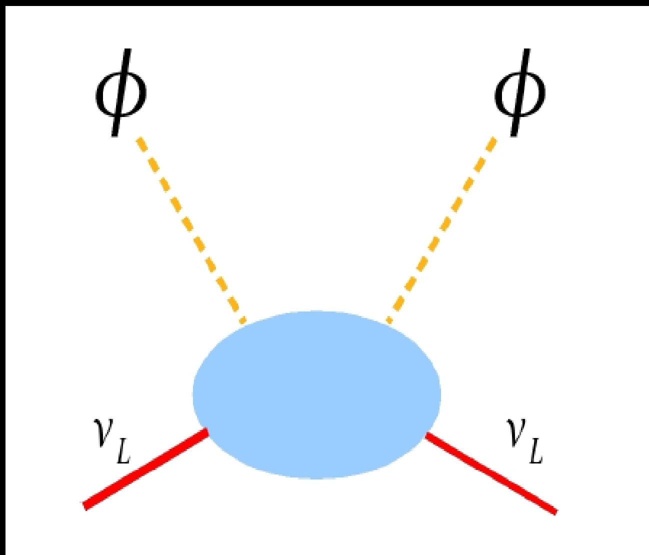


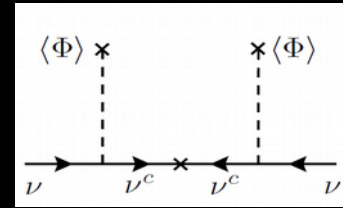
TYPE II

Schechter-Valle 80 & 82

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

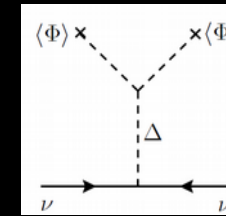
Origin of neutrino mass





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

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

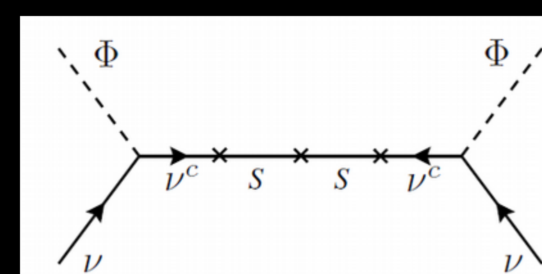
coefficient
mechanism
scale
flavor structure

any number m of singlet R's

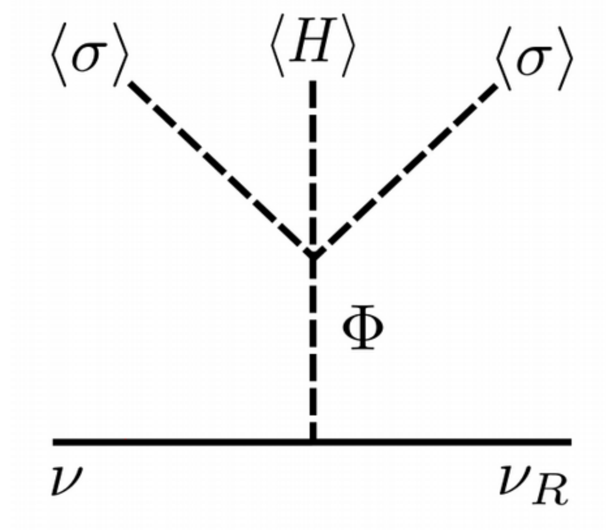
(3,2) (3,1) SCOTO-SEESAW (3,4) ...

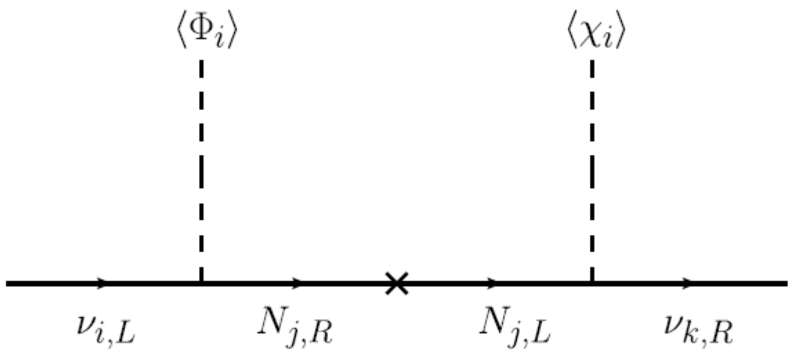
(3,6) LOW-SCALE SEESAW

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

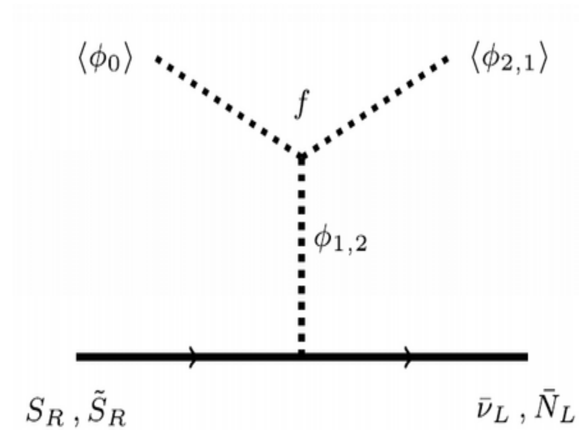
Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

type2

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



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

Phys.Lett. B755 (2016) 363-366

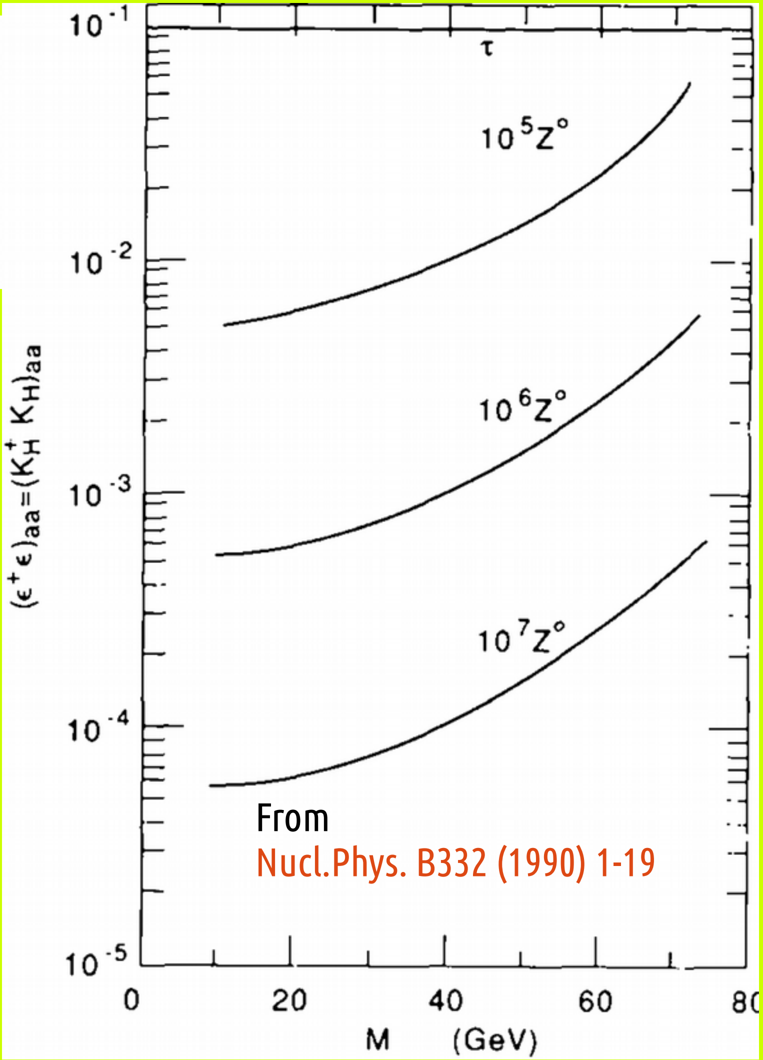
symmetry protects small neutrino mass

Phys.Rev. D98 (2018) 035009

Phys.Lett. B781 (2018) 122-128

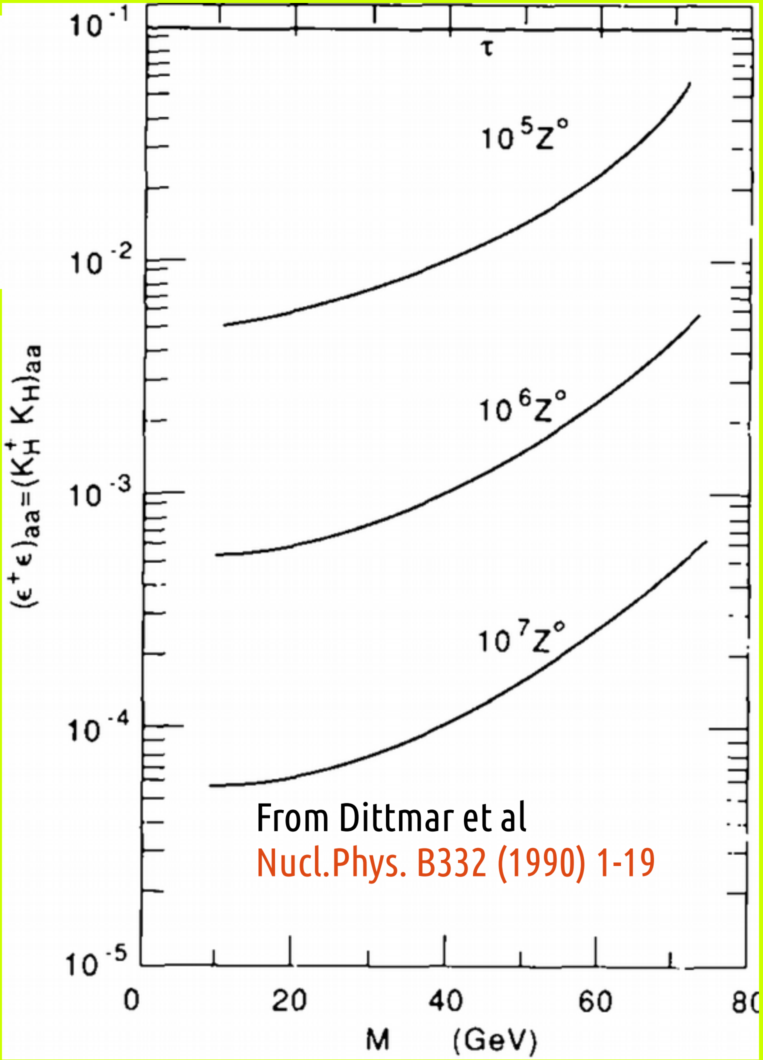
mediator searches

Coupling strength (Z → $N\bar{\nu}$ + $\bar{N}\nu$)

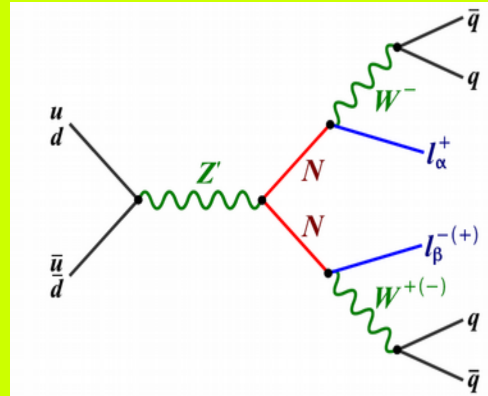


mediator searches — extended EW theory

Coupling strength (Z → N$\bar{\nu}$ + $\bar{N}\nu$)

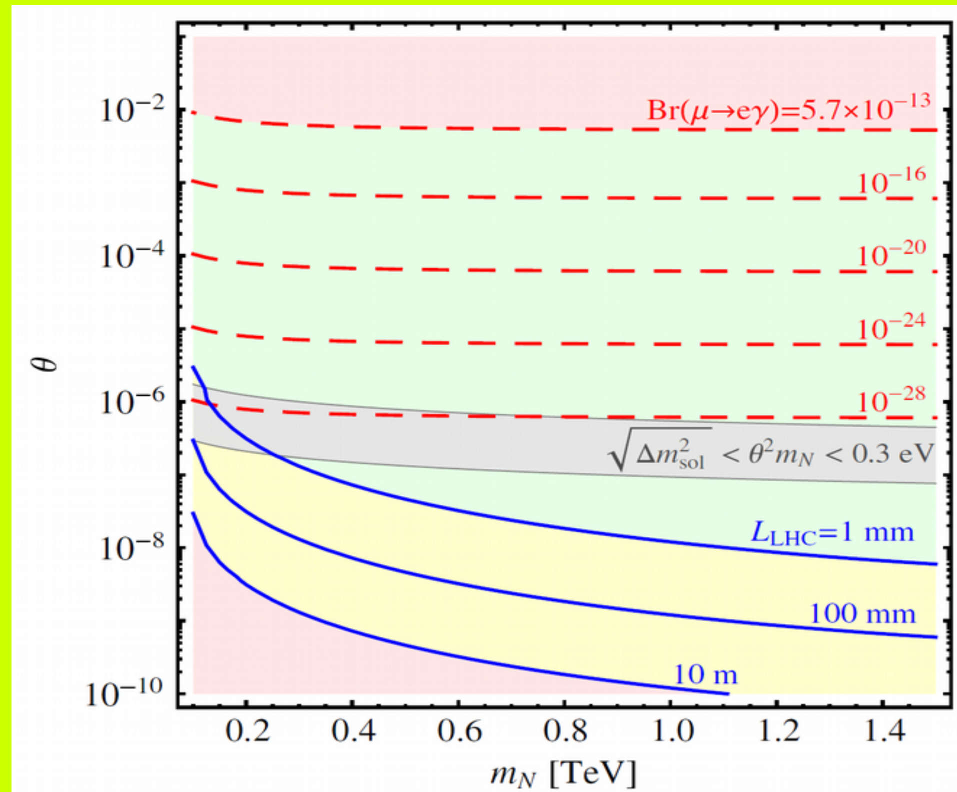


From Dittmar et al
Nucl.Phys. B332 (1990) 1-19



Review: Deppisch, Dev & Pilaftsis
New J.Phys. 17 (2015) 075019

charged lepton flavor violation as at HE



From Phys.Rev. D89 (2014) 051302
Also full LR Phys.Rev. D86 (2012) 055006

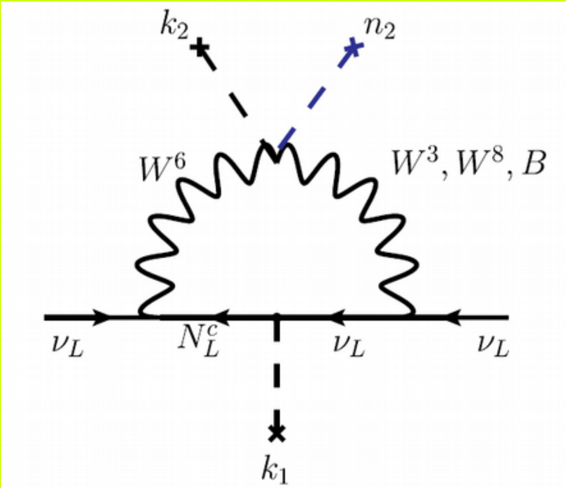
radiative neutrino mass in extended EW theory

331 motivation # families = # colours

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

calculable neutrino mass

Gauge nu-mass mediators



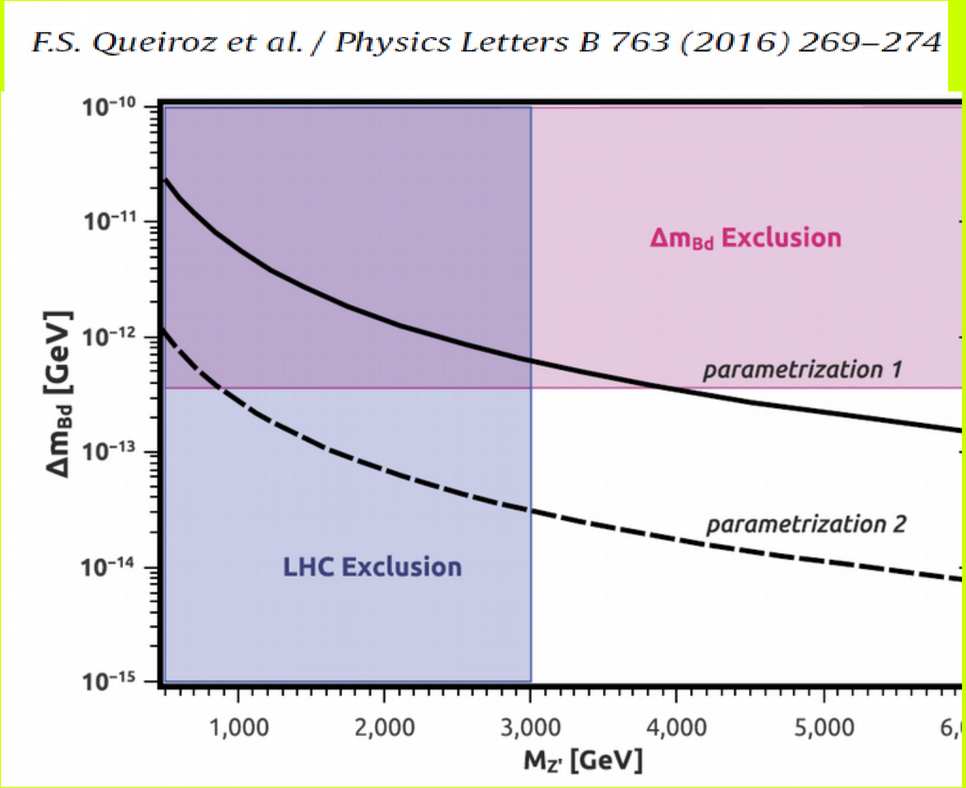
Boucenna, Morisi, JV Phys.Rev. D90 (2014) 013005

radiative neutrino mass in extended EW theory

331 motivation # families = # colours

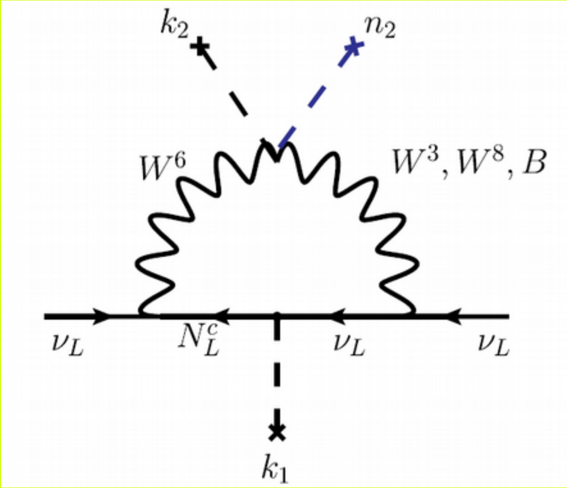
Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

low scale



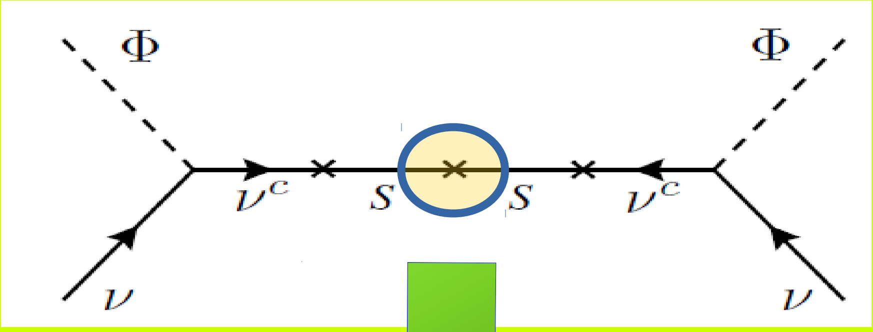
calculable neutrino mass

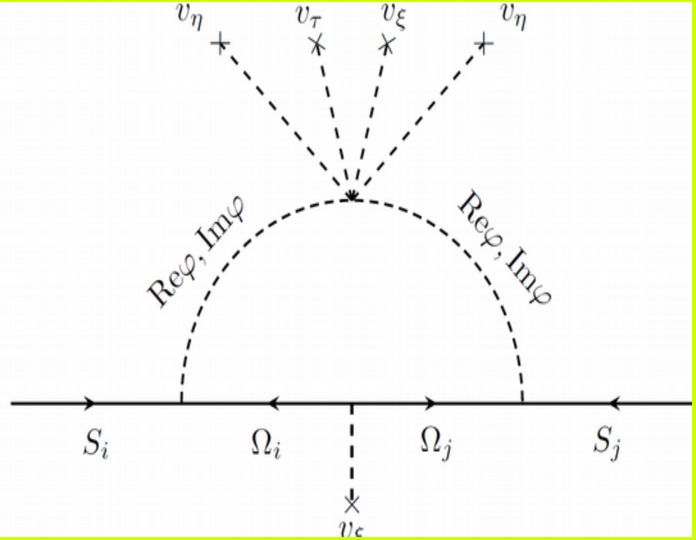
Gauge nu-mass mediators



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

combining low scale seesaw with radiative corrections



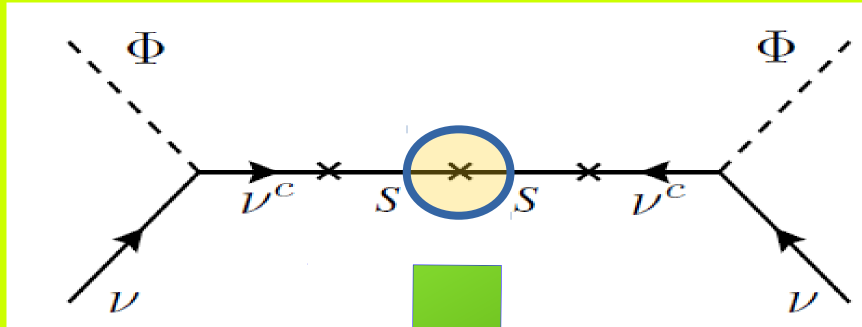


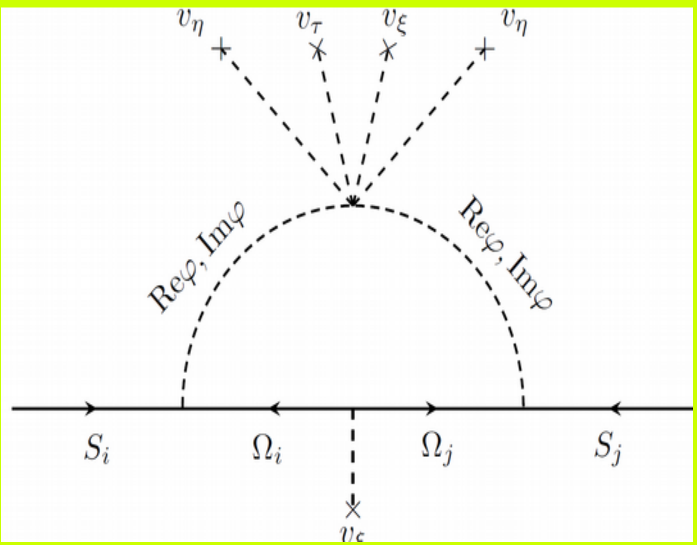
radiative inverse/linear seesaw

:Cárcamo Hernández et al JHEP 1902 (2019) 065

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

Combining low scale seesaw with radiative corrections





radiative inverse/linear seesaw

:Cárcamo Hernández et al JHEP 1902 (2019) 065

See also
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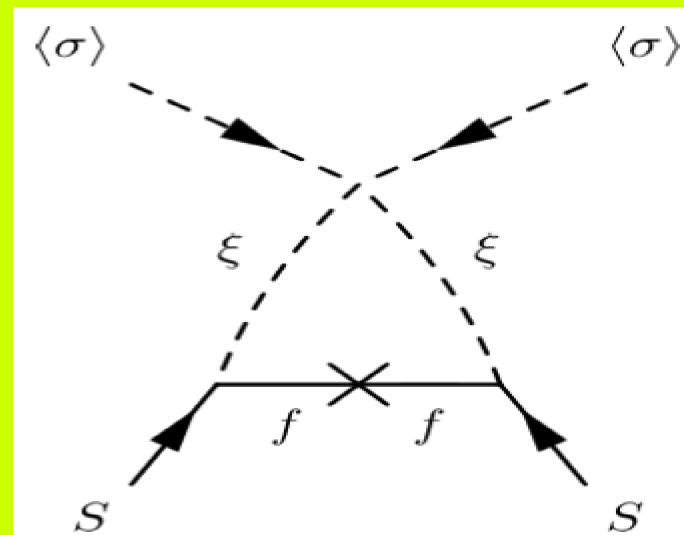
Ma 0904.4450
Baldes et al 1304.6162



scotogenic inverse seesaw

From arXiv:1907.07728

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

Simplest flavor symmetry

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

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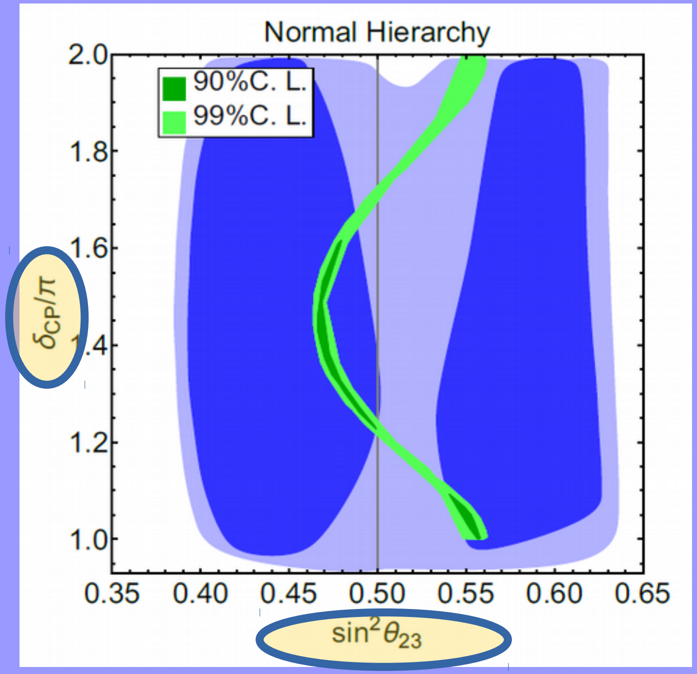
$$d_R \quad s_R \quad b_R$$

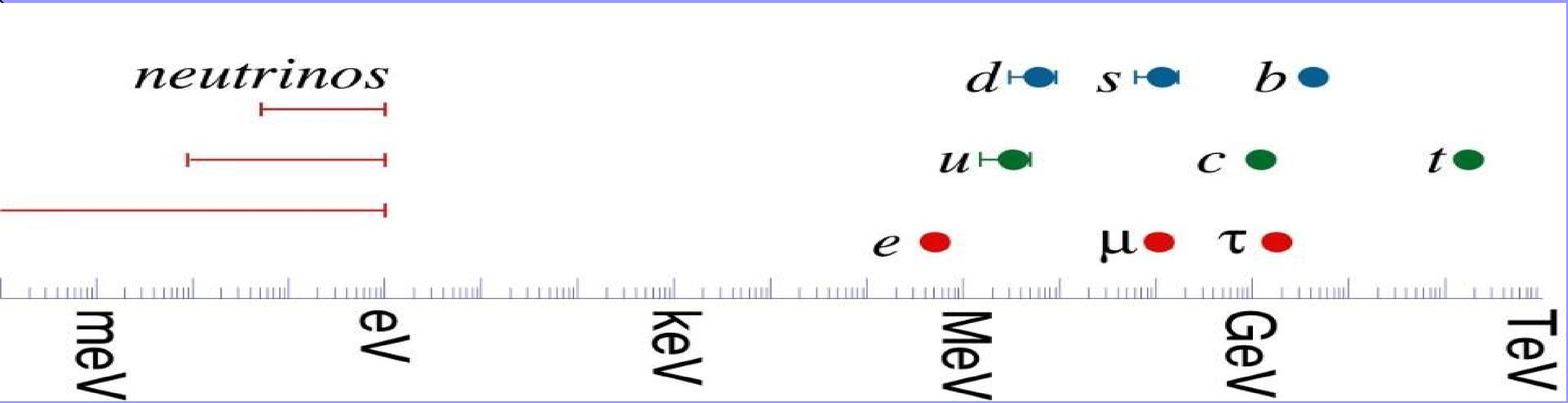
Babu-Ma-Valle PLB552 (2003) 207
Hirsch et al PRD69 (2004) 093006

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

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

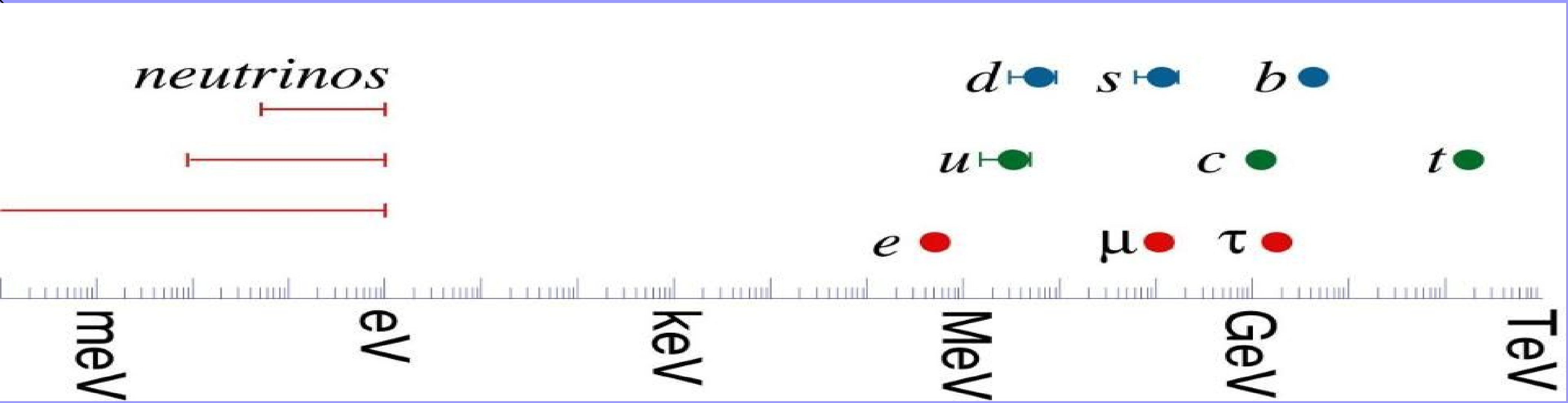


to be probed at LBL experiments, e.g. DUNE...



from oscillations to

charged fermion masses



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

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

Warped SM with flavor

:Chen et al
JHEP01(2016)007

mass hierarchies from geometry

Warped SM With flavor

:Chen et al
JHEP01(2016)007

mass hierarchies from geometry

⇨ angles related by symmetry

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

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

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

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

⇨

Warped SM with flavor

constrained global fitting

Chen et al
JHEP01(2016)007

mass hierarchies from geometry

angles related by symmetry

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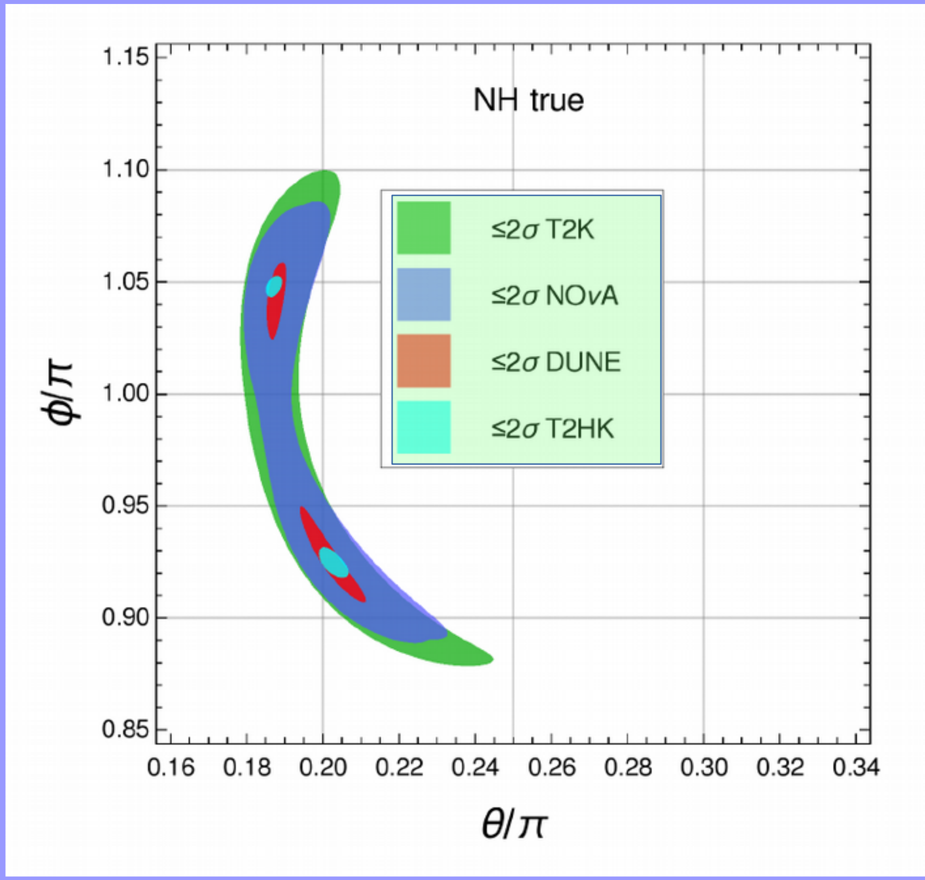
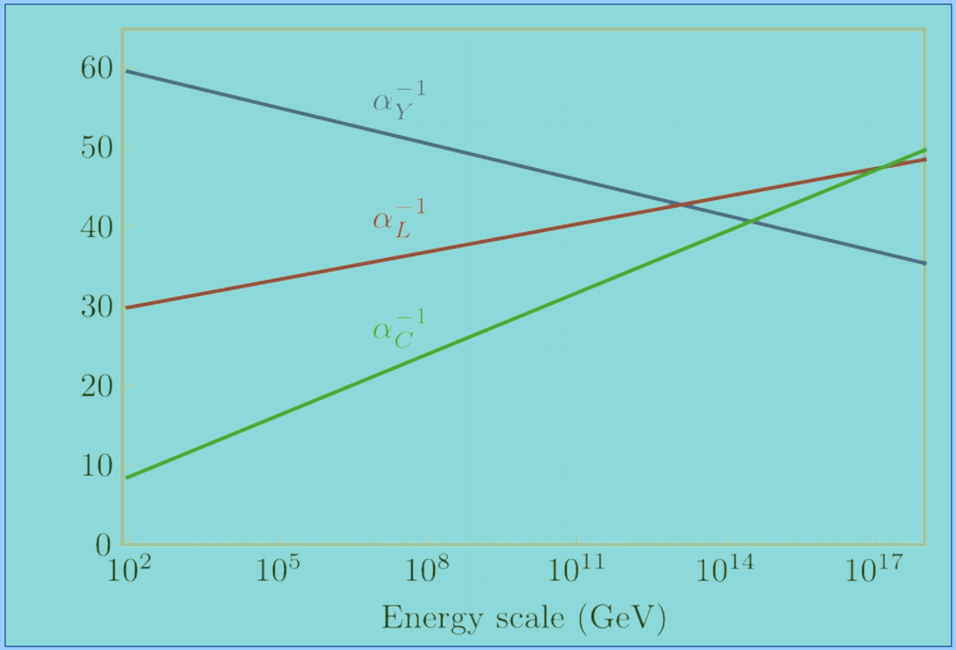


Predictions for LBL experiments
Phys. Rev. D95 (2017) 095030
Phys.Lett. B771 (2017) 524

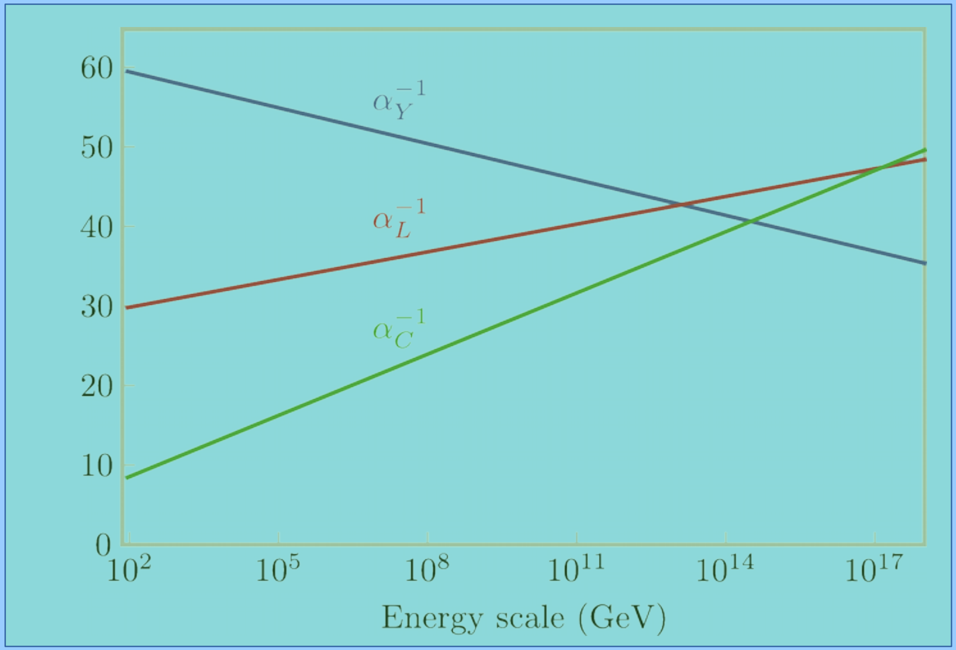
Standard model



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** …

Standard model



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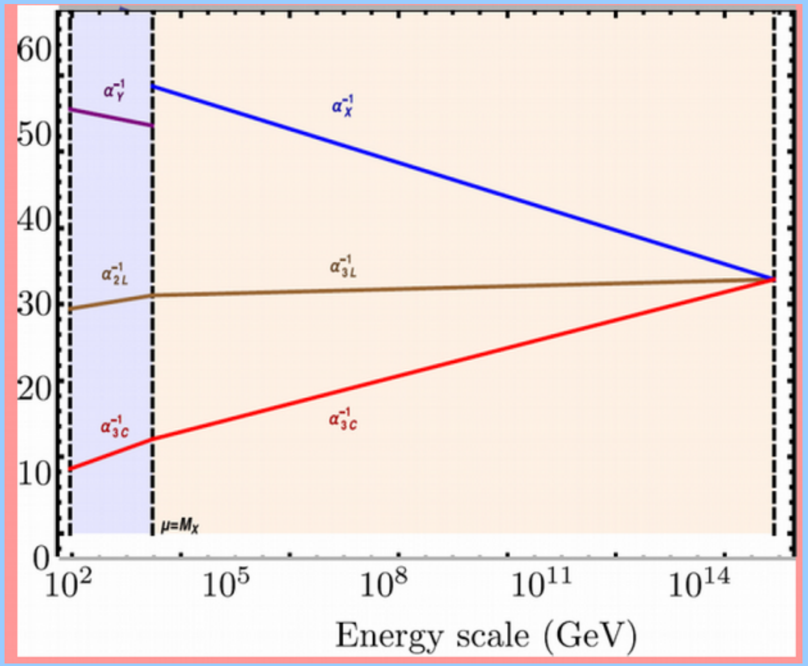


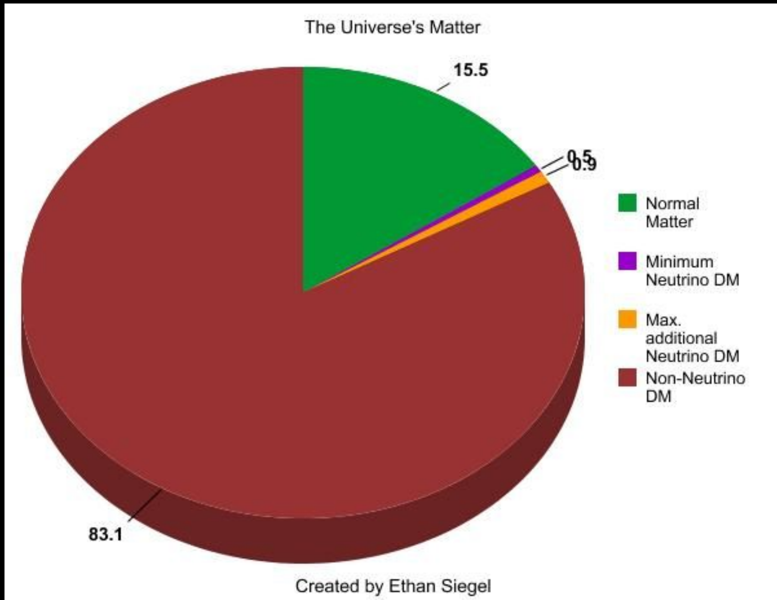
neutrinos & unification

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

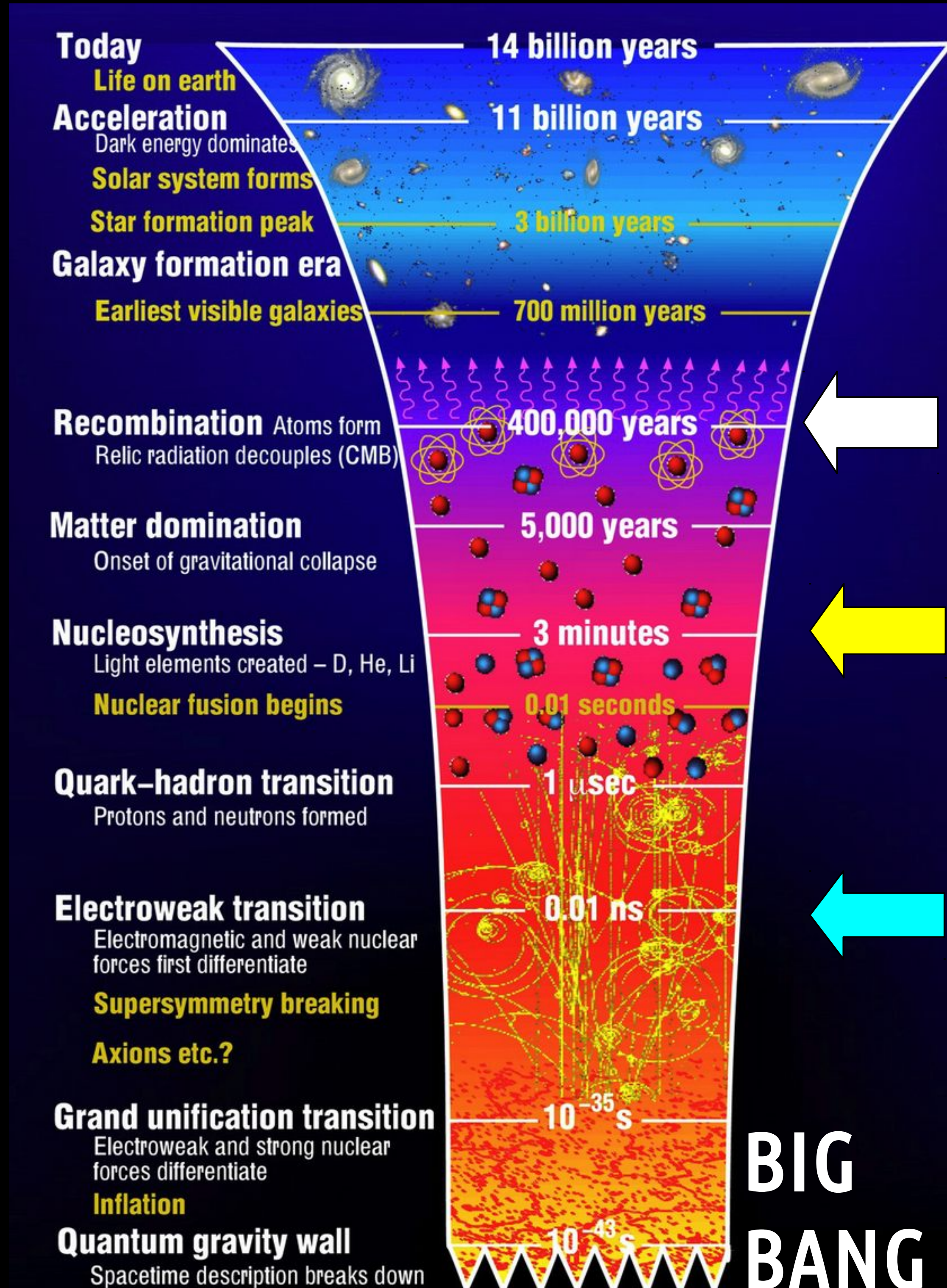
E(6) F-theory GUT

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

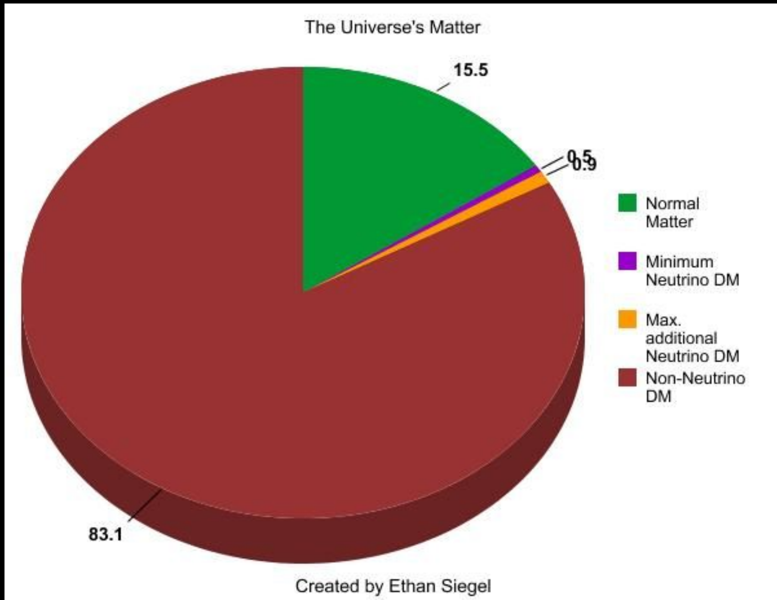
Deppisch et al Phys.Lett. B762 (2016) 432



need for dark matter

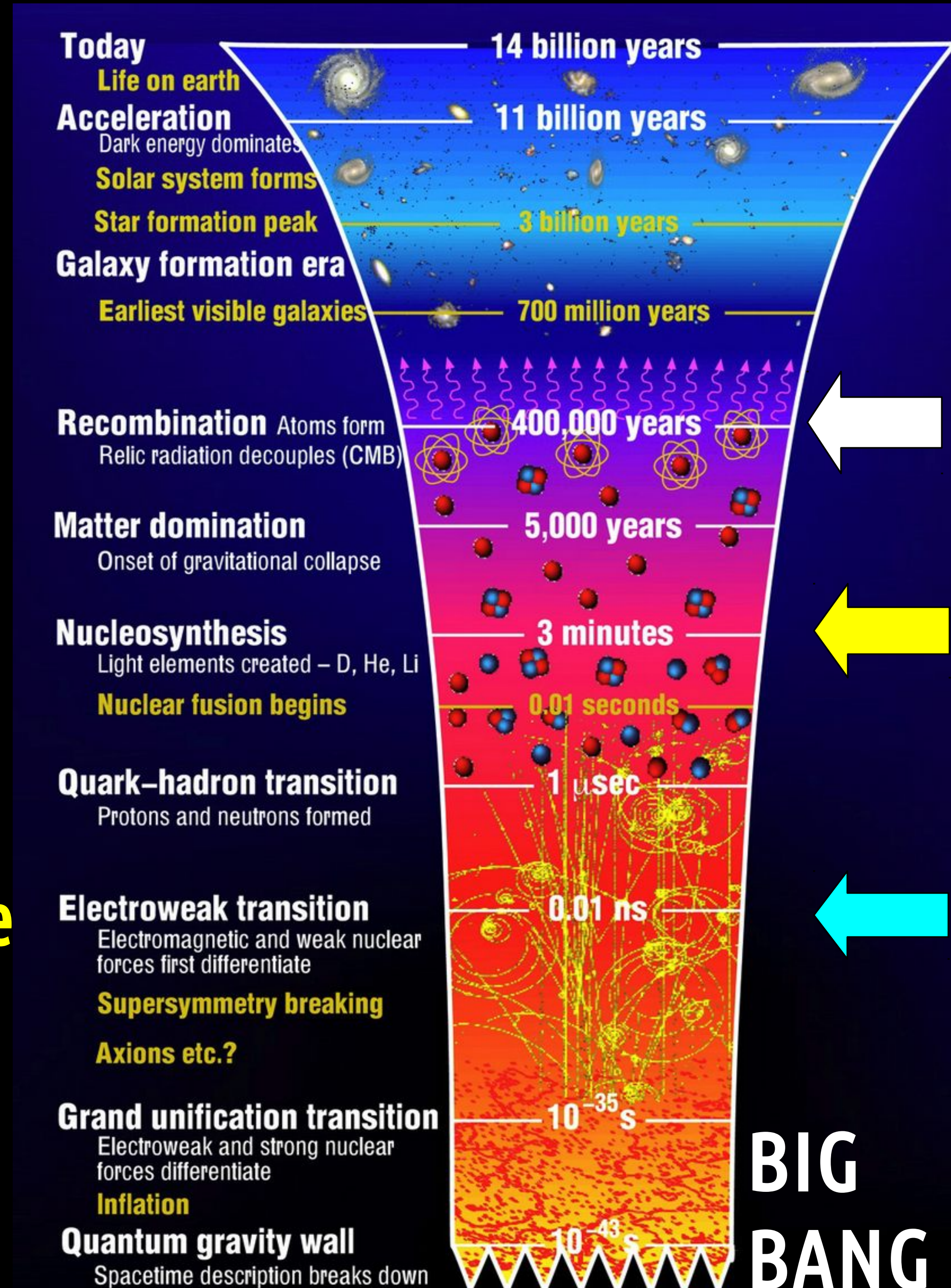


BIG BANG

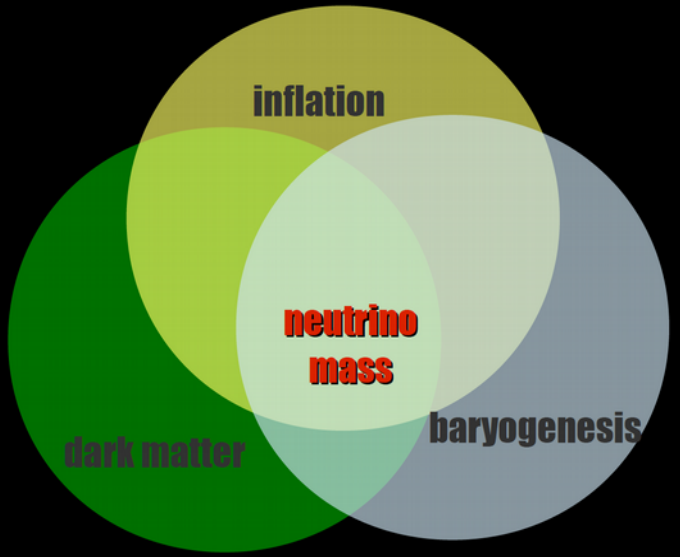


need for dark matter

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



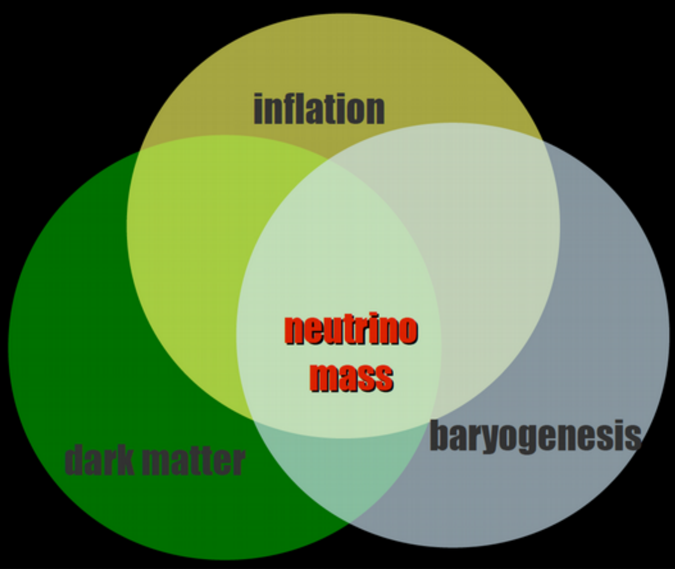
neutrino mass generation may be key to DM and other cosmological puzzles

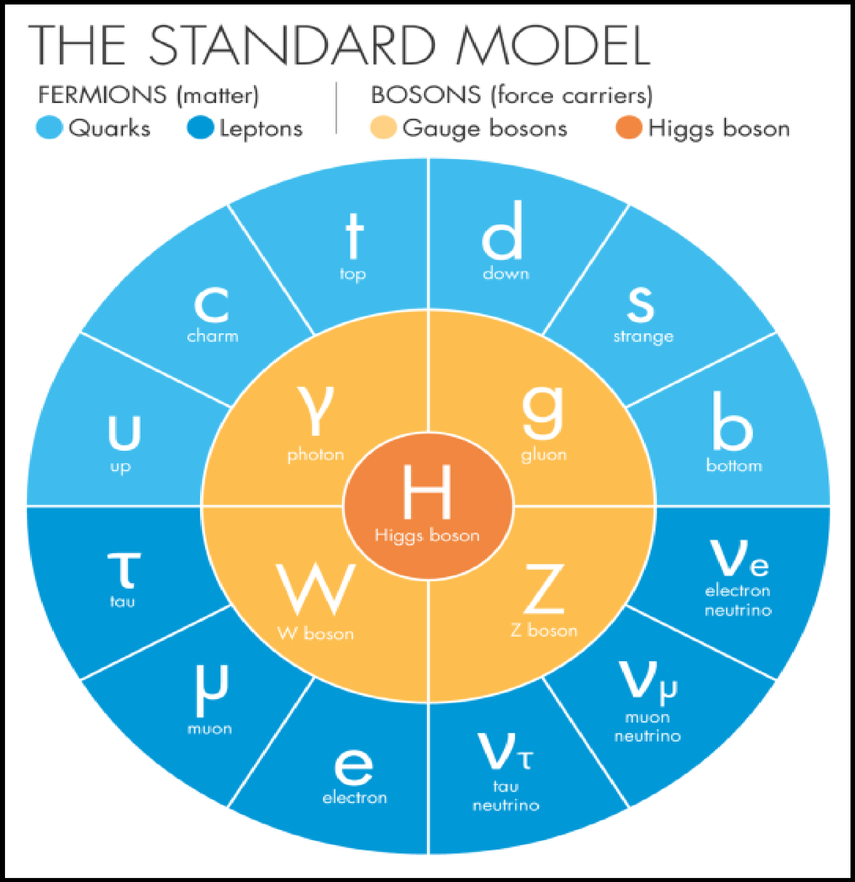


take home

- 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

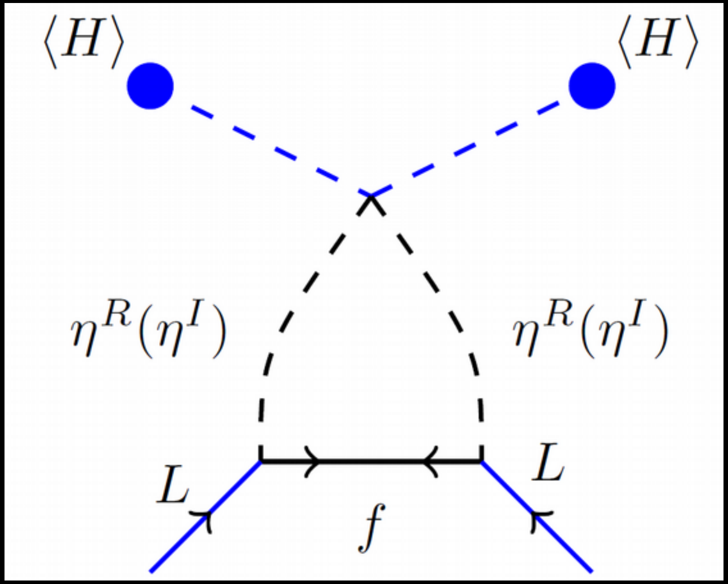
neutrino mass generation may be key to DM and other cosmological puzzles





THE END

Back-ups

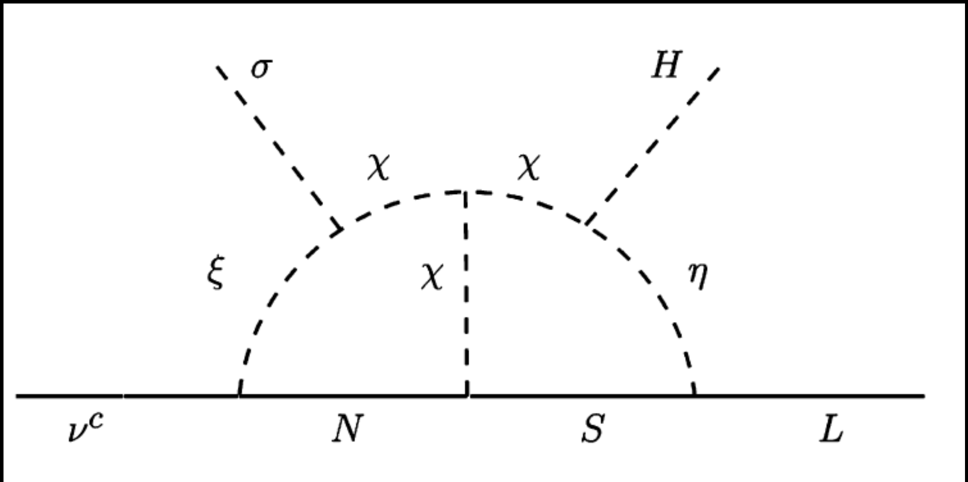


E Ma 2006 "scotogenic"
Hirsch et al JHEP 1310 (2013) 149
Merle et al JHEP 1607 (2016) 013
Diaz et al JHEP01(2016)007

WIMP dark matter as neutrino mass mediator

→ Z2 preserved by RGE

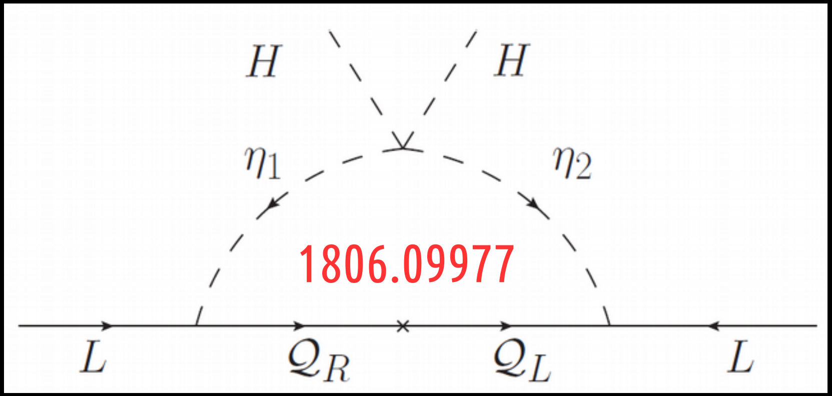
many variants, e.g.



Phys.Lett. B762 (2016) 214-218

See also scotogenic with
Gauged matter parity arXiv:1902.05966

dark matter as bound-state of neutrino mass mediator



Reig, Restrepo, Valle, Zapata

De Luca, Mitridate, Redi, Smirnov, Strumia

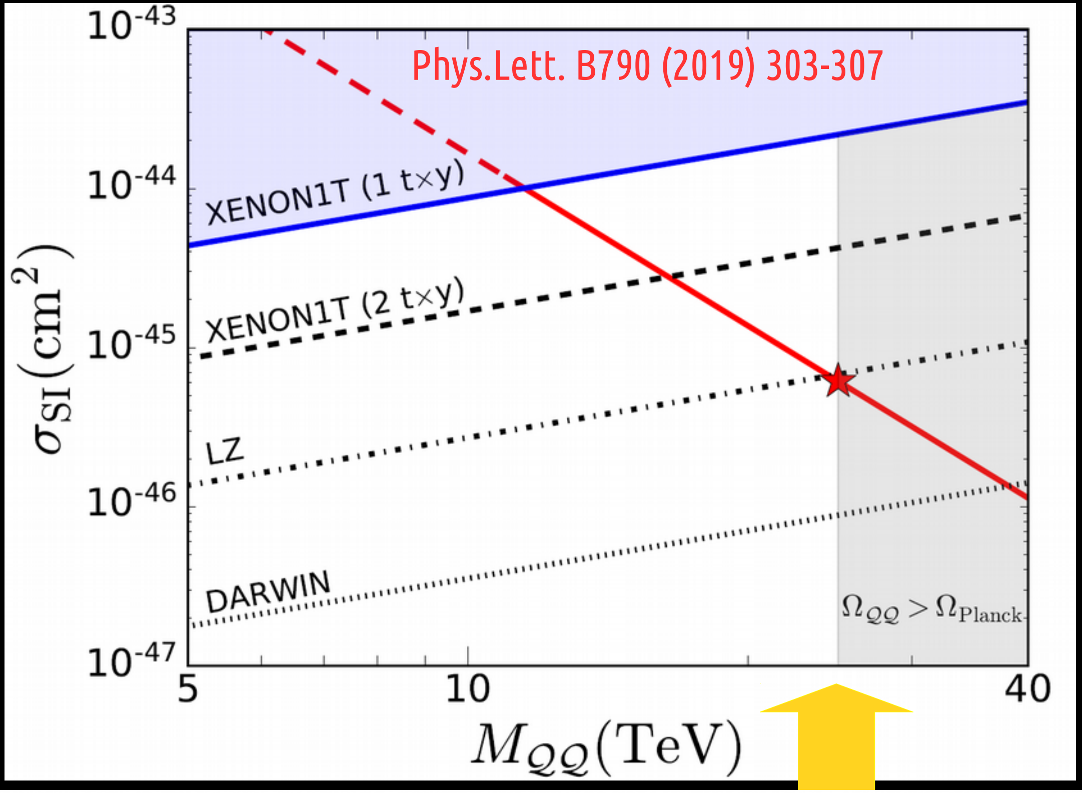
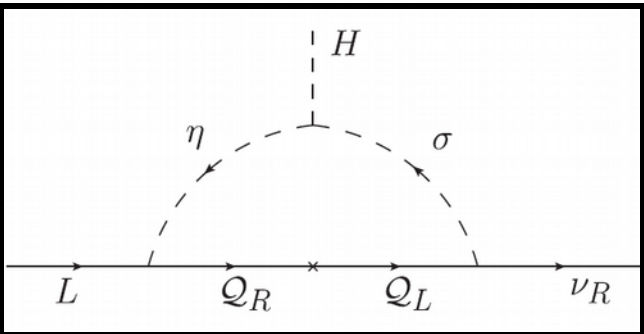


FIG. 2. Spin-independent cross section as a function of $M_{QQ} = 2M_Q$ (red). The star represents the mass required for a thermal bound state 25 TeVdark matter. Lower values can be probed by direct searches, the current bound is indicated in blue, while the black lines (dashed, dotted and dot-dashed)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



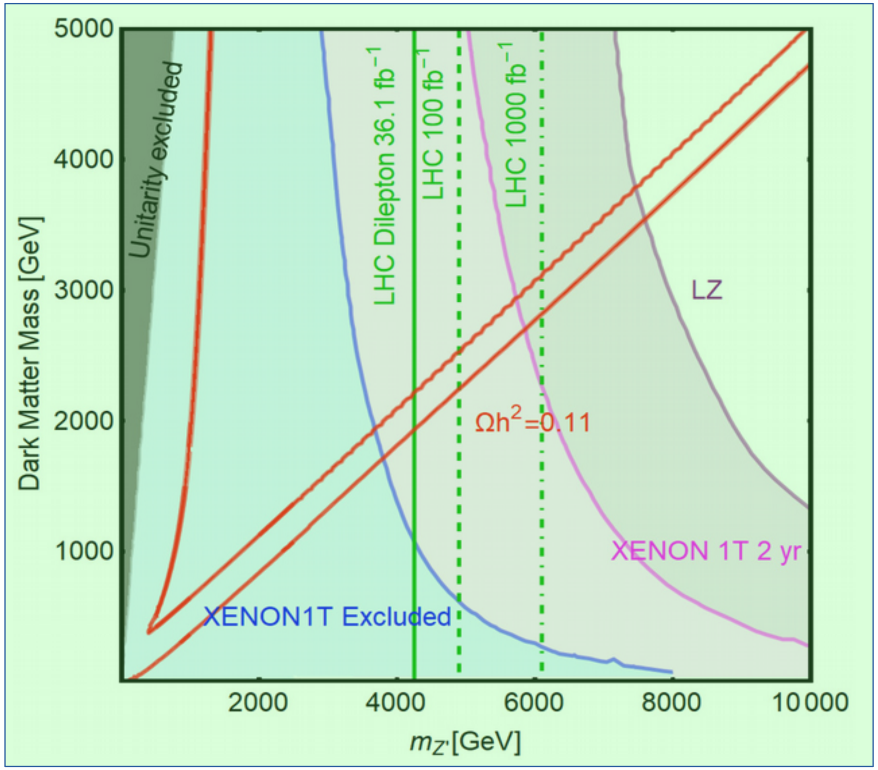
Phys.Rev. D97 (2018) 115032

DM stability from Diracness

cosmology from seesaw

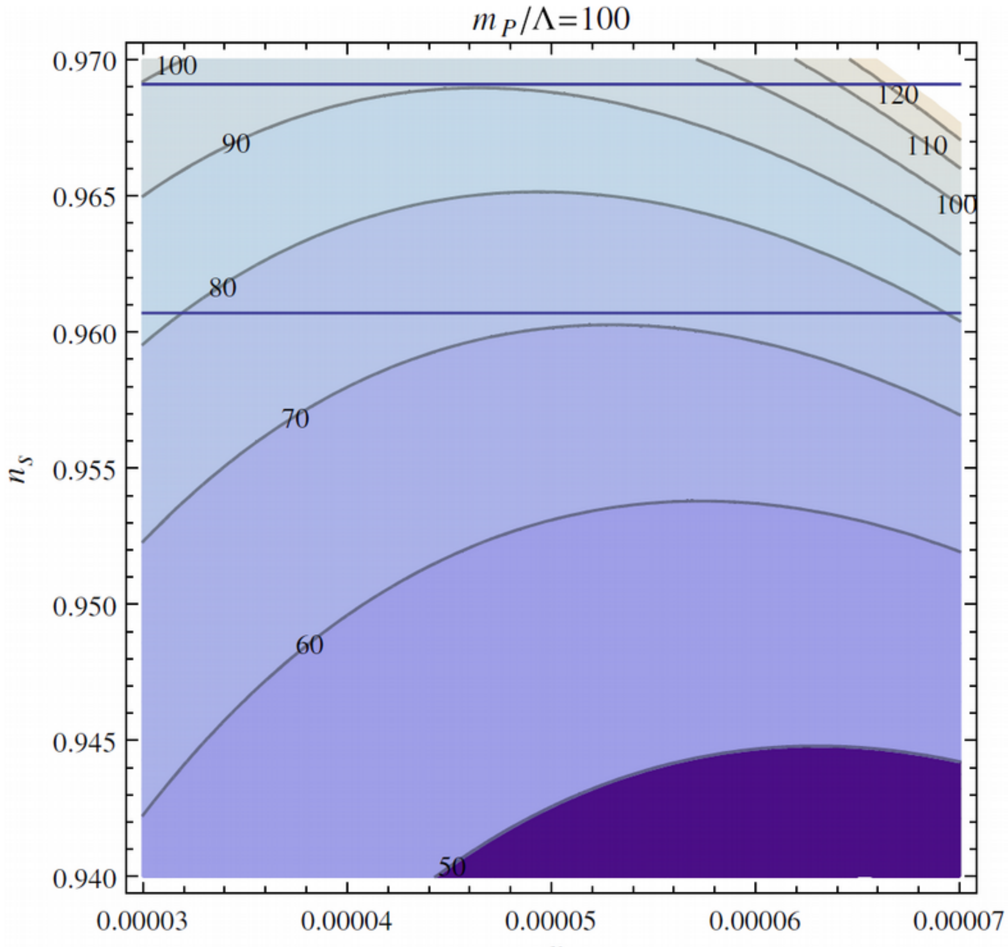
Alves et al   Phys.Lett. B772 (2017) 825–83

WIMP Dirac dark matter



DM stability from gauge matter parity

From Phys. Rev. D 99, 055040 (2019)



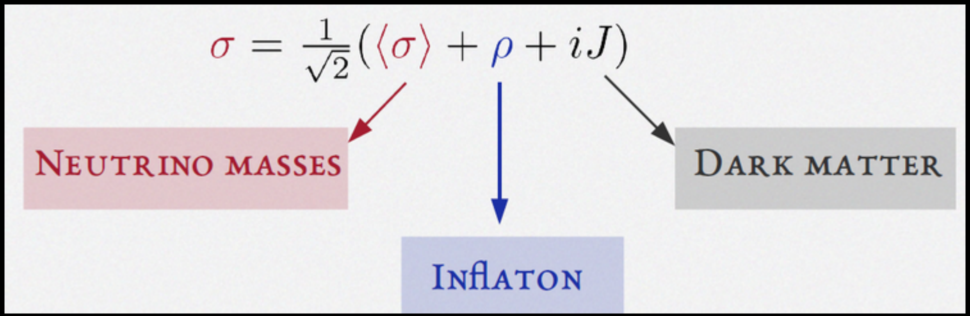
Asymmetric Dark Matter, Inflation and Leptogenesis from B-L Symmetry Breaking

majoron dark matter

Berezinsky, Valle PLB318 (1993) 360

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

Aristizabal et al JCAP 1407 (2014) 052



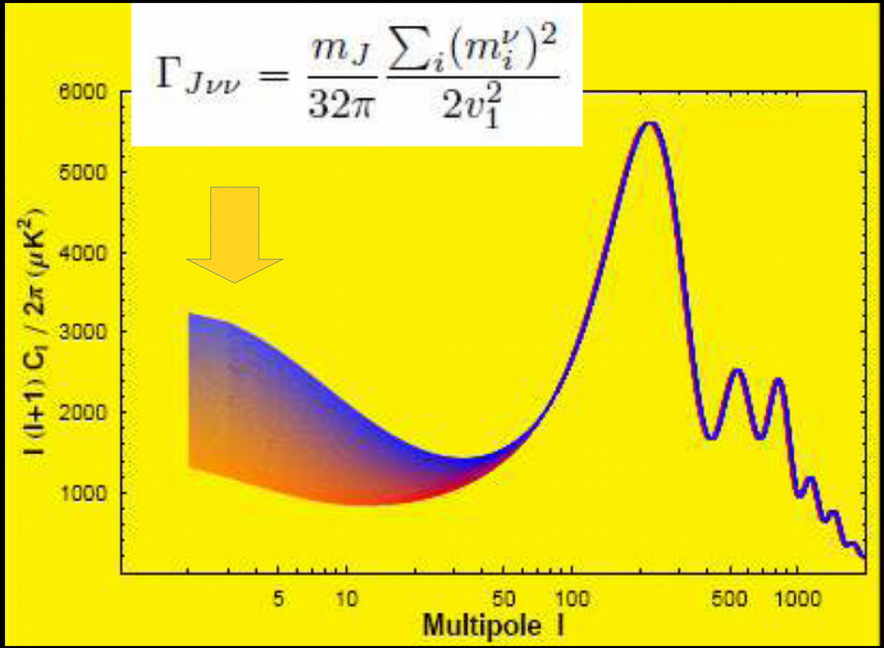
seesaw leptogenesis & inflation

X-rays from DM decay

Bazzocchi & al JCAP 0808 (2008) 013
Esteves et al, PRD 82, 073008 (2010)
Lattanzi et al PRD88 (2013) 063528

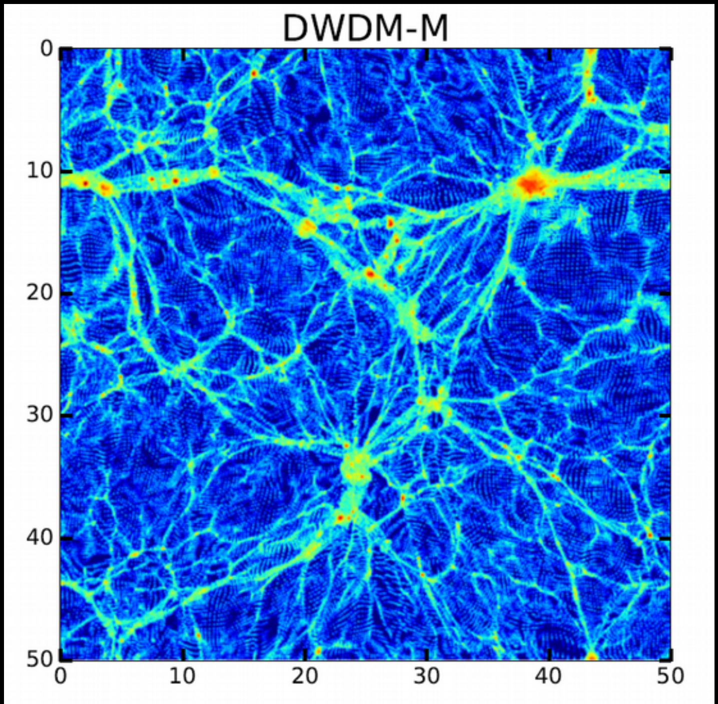
Consistency with CMB

Lattanzi & Valle, PRL99 (2007) 121301



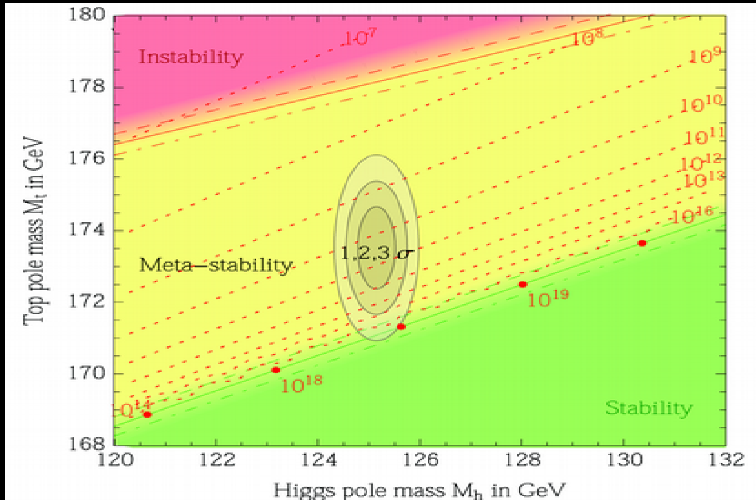
large
scale
structure

Kuo et al
JCAP 1812 (2018) 026

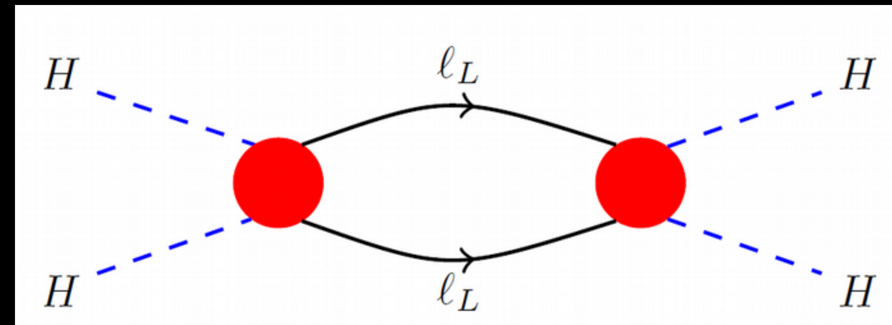


Reig, Yamada, Valle arXiv:1905.01287

neutrino mass & EW vacuum



From Buttazzo et al: JHEP 1312 (2013) 089

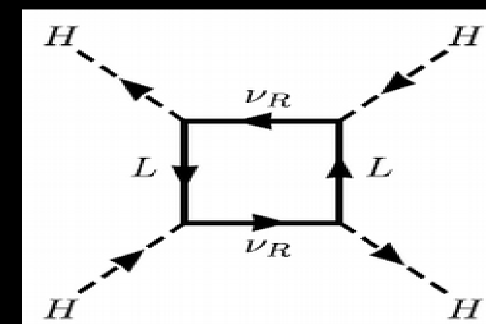


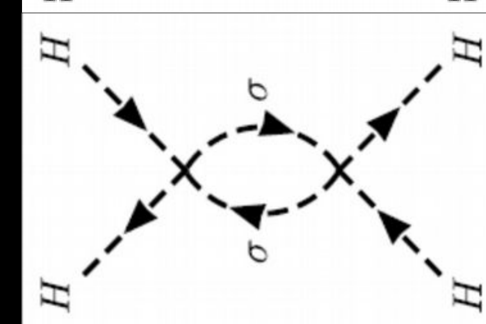
Higgs searches **Bonilla et al**

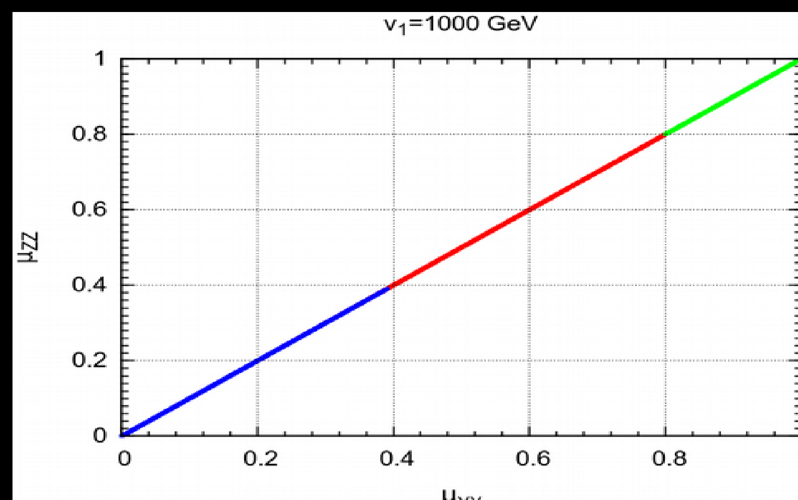
Phys.Lett. B756 (2016) 345-349

New J. Phys. 18 (2016) 033033

Phys.Rev. D91 (2015) 113015







EW consistency also requires perturbative unitarity, etc

Phys.Rev. D92 (2015) 075028

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

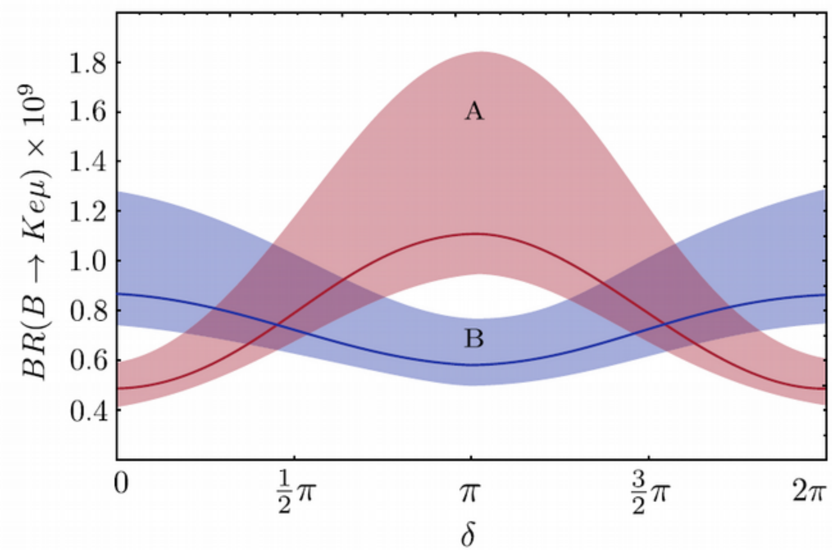
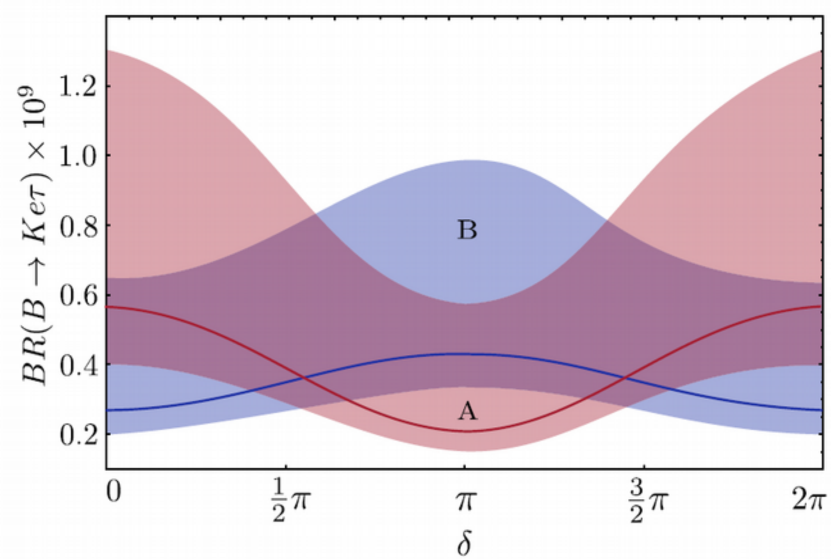
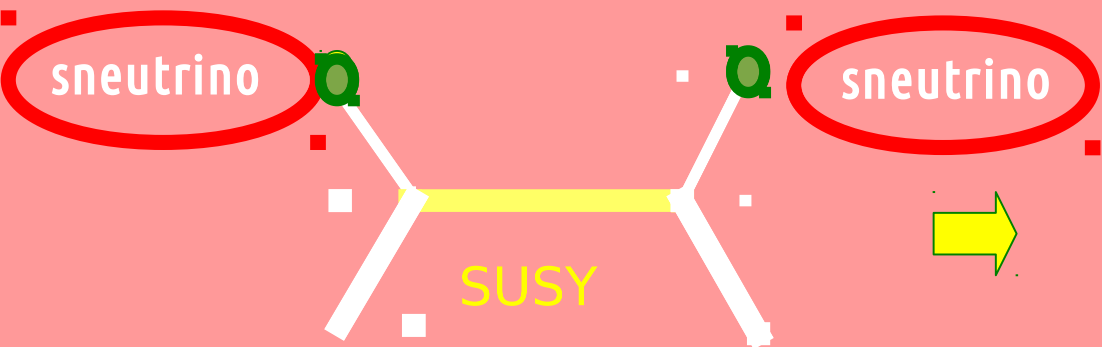


Fig. 1. The branching ratio of the decay $B \to Ke\mu$ versus the CP violating phase δ in scenarios A and B. The bands are obtained by taking the leptonic mixing angles within their 1σ range w.r.t. the best-fit value (solid line) [26].



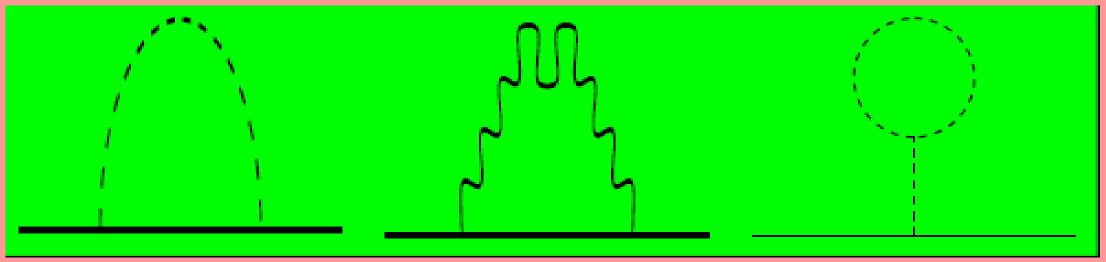
susy origin of neutrino mass

Masiero & Valle, PLB251 (1990) 273
Bhattacharyya & Pal, PRD82 (2010) 055013



EFF. BILINEAR RPV

ATM SCALE
SUSY-SEESAW



SOLAR SCALE
RADIATIVE

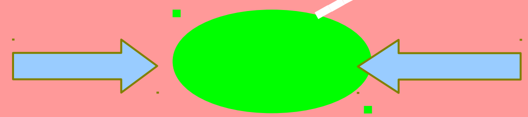
Diaz et al PRD68 (2003) 013009, PRD62 (2000) 113008

Bazzocchi et al JHEP 01 (2013) 033 arXiv:1202.1529

LIGHTEST NEUTRALINO DECAYS from cascade squark & gluino decays

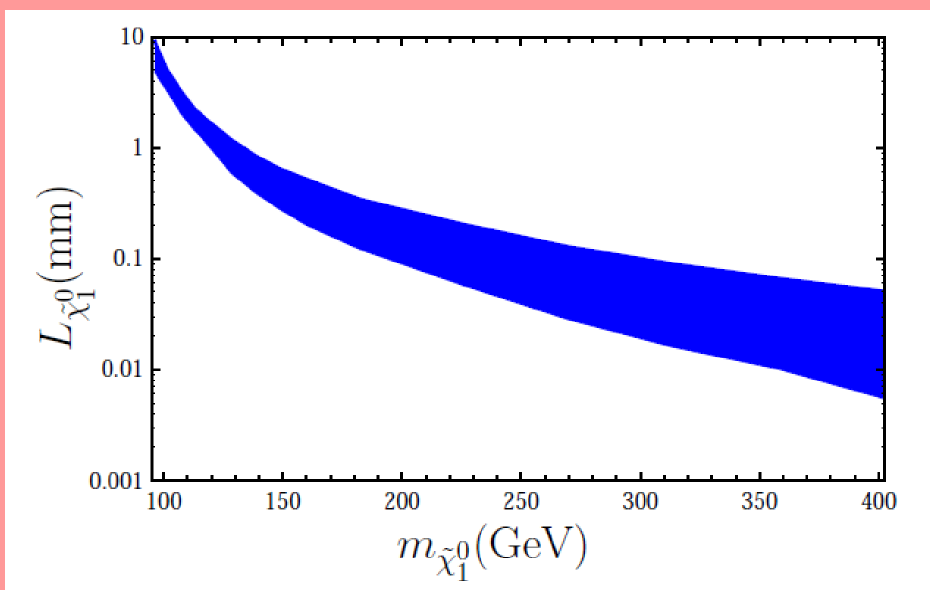
De Campos et al
Phys.Rev. D86 (2012) 075001

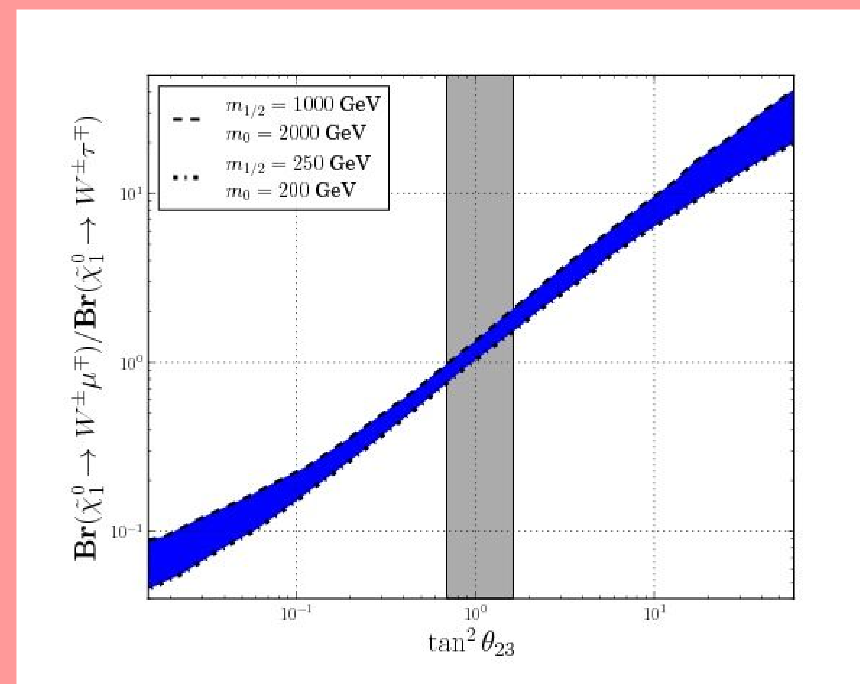
$\tilde{\chi}_1^0 \to W^{\pm} l_i^{\mp}$ $\tilde{\chi}_1^0 \to Z^0 \nu_i$



Lightest neutralino decay correlates with atm angle

Lightest neutralino decay length





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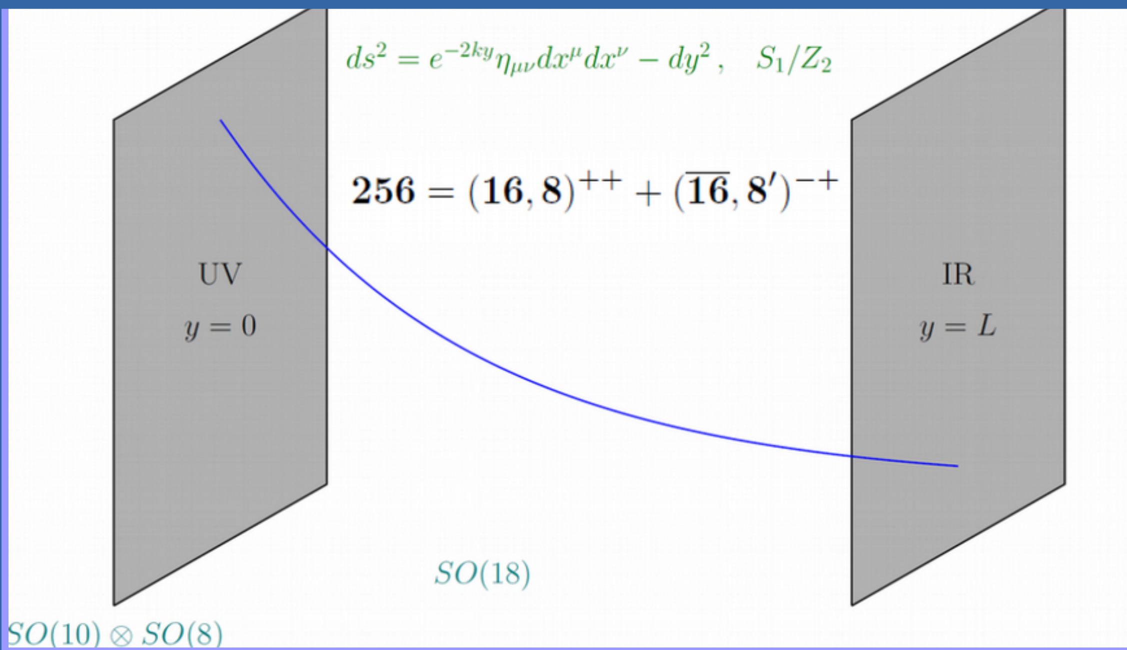
PROBING NUS @ LHC

Unifying forces & families

inspired by beauty of neutrinos in SO10

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

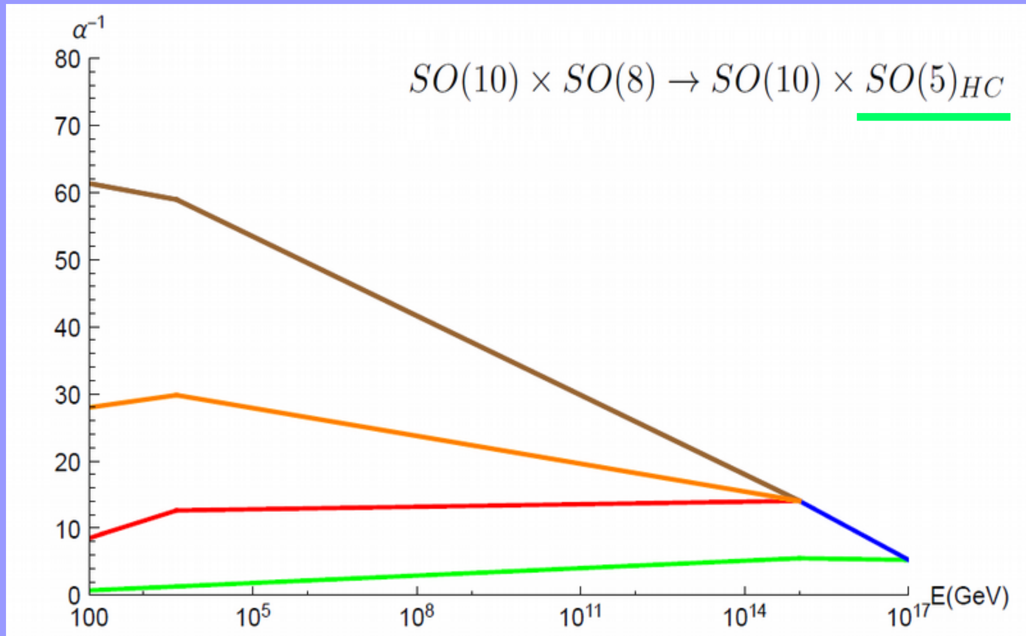
Reig, Valle, Vaquera-Araujo, Wilczek
Phys.Lett. B774 (2017) 667-670



promote M4 to AdS5 & use orbifold BC to decouple mirrors

unwanted chiral families bound
by new hypercolor force above TeV

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