neutrino physics update

JOSÉ W F VALLE

VIII international conference on High Energy Physics in the LHC Era

9–13 de enero de 2023
Universidad Técnica Federico Santa María

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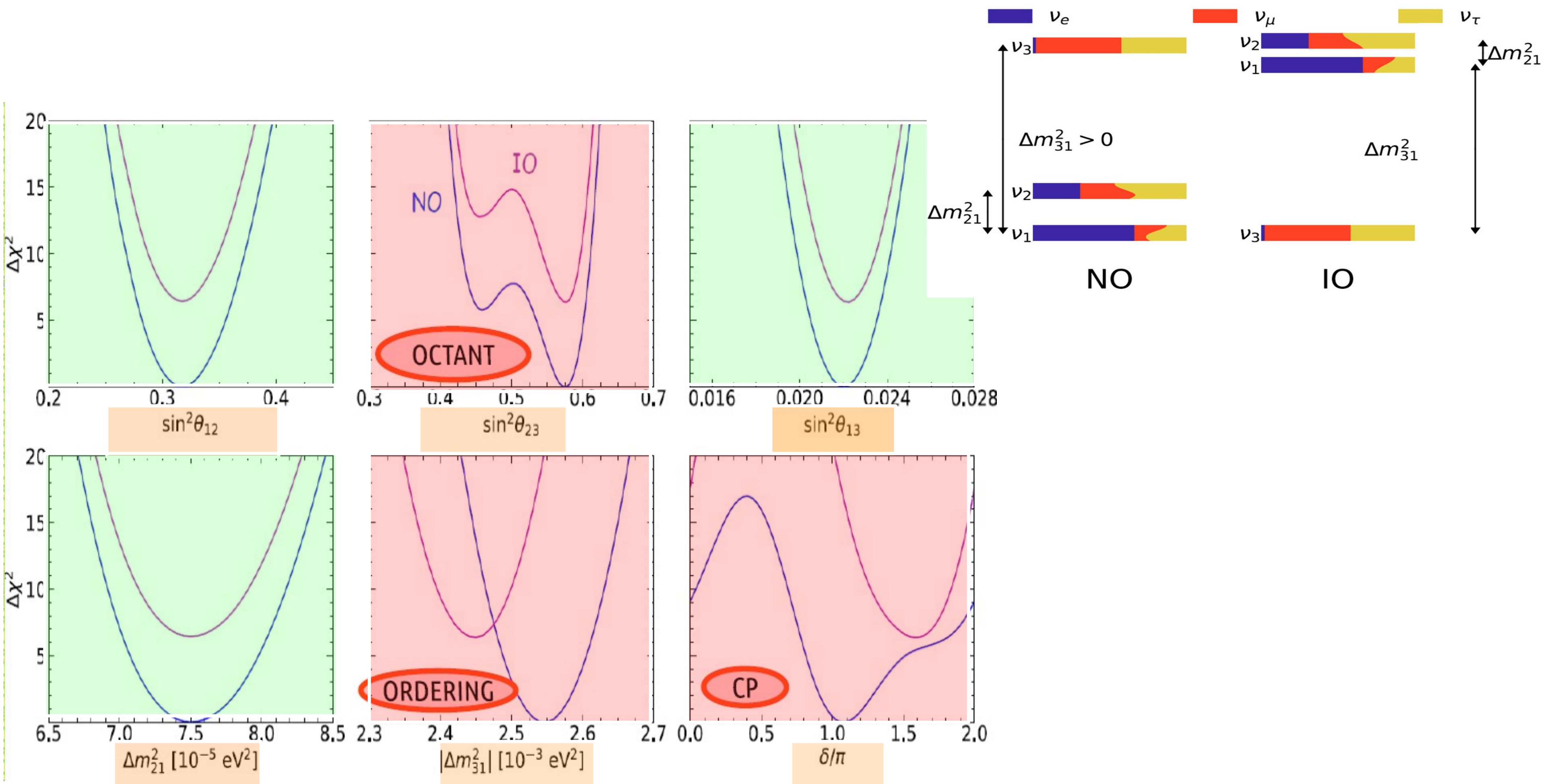
neutrino oscillations

PF de Salas et al JHEP02(2021)071

https://zenodo.org/record 4593330#.YfoBVWNKjIo



Similar results from Bari and NuFit groups

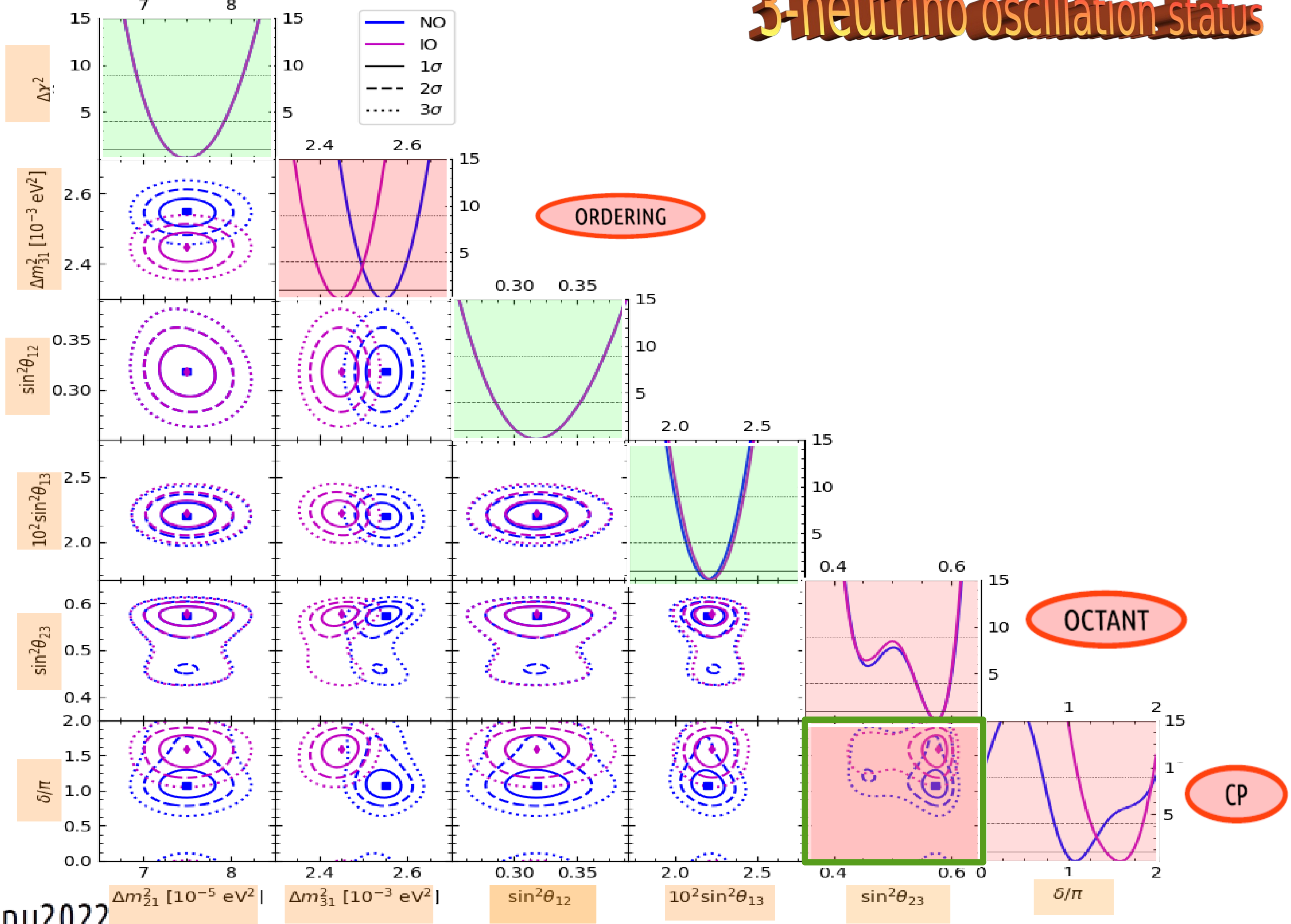
@jwvalle2

3-neutrino oscillation status

PF de Salas et al JHEP02(2021)071

https://globalfit.astroparticles.es/

https://zenodo.org/record 4593330#.YFoBVWNKjIo



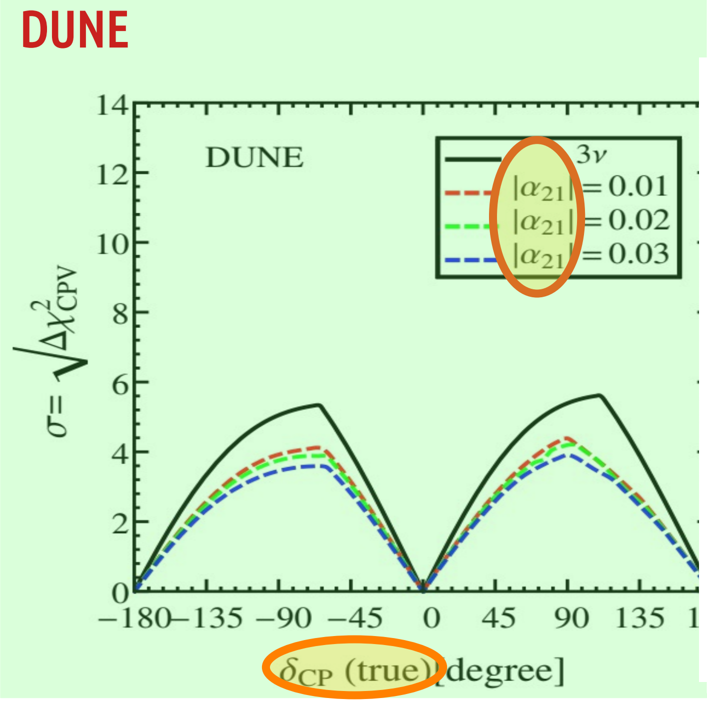
Updates from nu2022

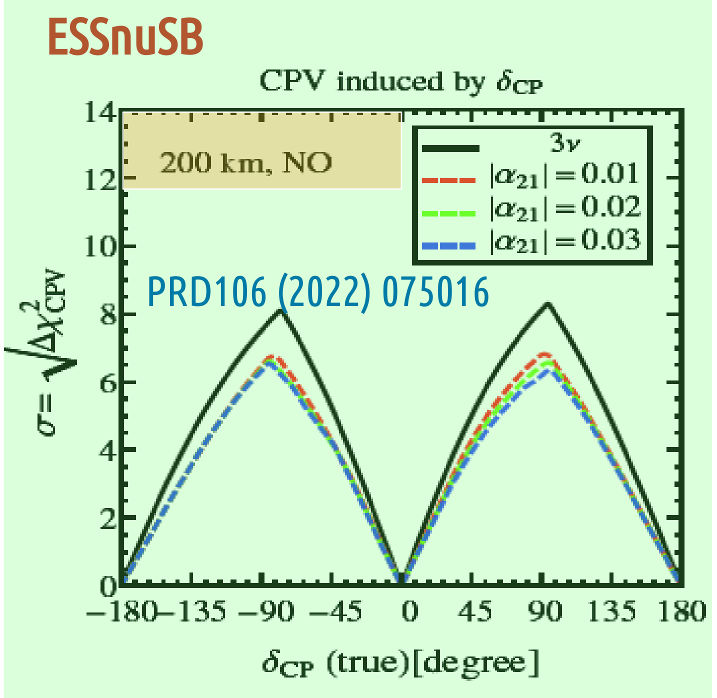
$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024} \quad \text{(2.8\% precision)}$$

@jwvalle3

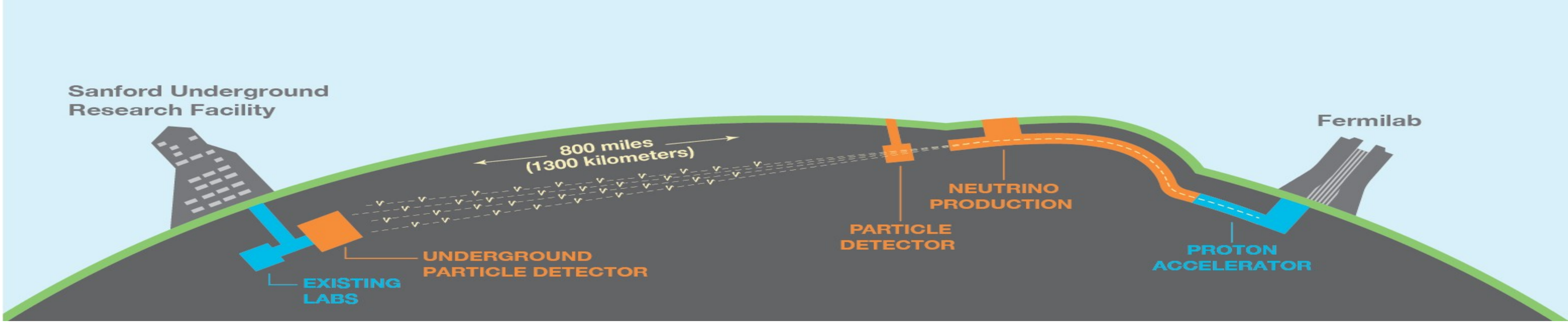
CPV

PhysRevLett117(2016)061804
New J.Phys. 19 (2017) 9, 093005
PhysRevD97 (2018) 095026
2008.12769





Expected CP discovery Sensitivity: standard 3-nu vs Unitarity violation



CPV reviews	Nunokawa, Parke, Valle	Prog.Part.Nucl.Phys. 60 (2008) 338
	Branco, Felipe, Joaquim,	Rev.Mod.Phys. 84 (2012) 515

@jwvalle4

TBM interpretation

Harrison,
Scott
& Perkins
2002

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

θ_{13}

CP

Phys.Rev.D98(2018)055019

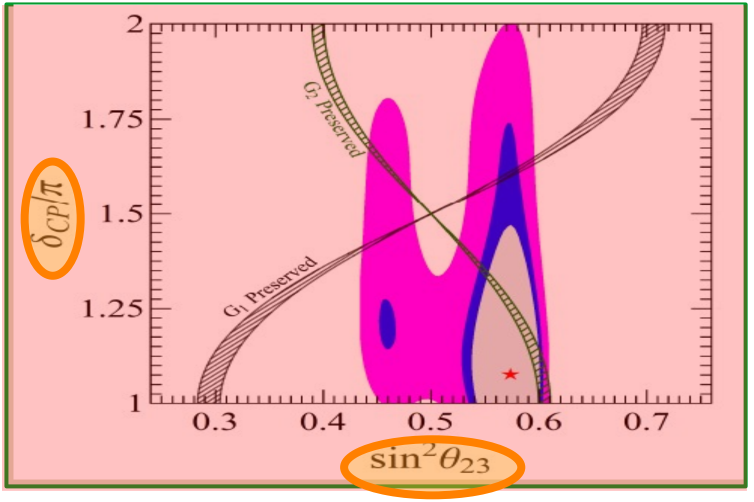
$$\sin^2\theta_{12}\cos^2\theta_{13} = \frac{1}{3}\,,$$

$$\tan 2\theta_{23}\cos\delta_{CP} = \frac{\cos 2\theta_{13}}{\sin\theta_{13}\sqrt{2-3\sin^2\theta_{13}}}$$

systematic revamping

Chen et al
Phys.Lett. B753 (2016) 644
Phys.Rev. D94 (2016) 033002
JHEP 1807 (2018) 077
Phys.Lett. B792 (2019) 461
Phys.Rev. D99 (2019) 075005

an example



Bi-Large lepton mixing pattern

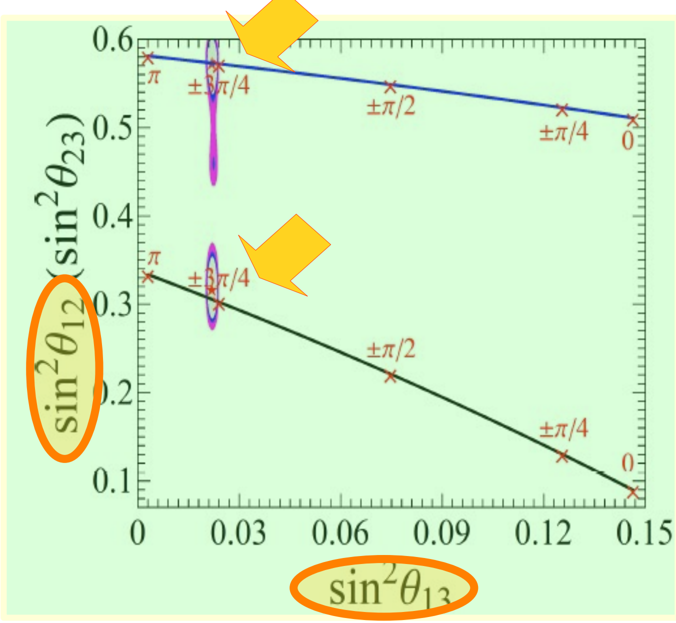
$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & -\lambda e^{i\phi} & A\lambda^3 e^{i\phi} \\ \lambda e^{-i\phi} & 1-\frac{1}{2}\lambda^2 & -A\lambda^2 \\ 0 & A\lambda^2 & 1 \end{bmatrix} \quad \begin{bmatrix} 1-\frac{5\lambda^2}{2} & 2\lambda & -\lambda \\ -2\lambda+3\lambda^2 & 1-\frac{13\lambda^2}{2} &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

Largest Q-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

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

predicting solar & atm



From Phys.Lett. B792 (2019) 461

looser realization
Phys.Lett.B 796 (2019) 162

Many other patterns, e.g. TM1, TM2, GR most can be probed at DUNE or T2HK

e.g. Phys.Rev.D97(2018)095025

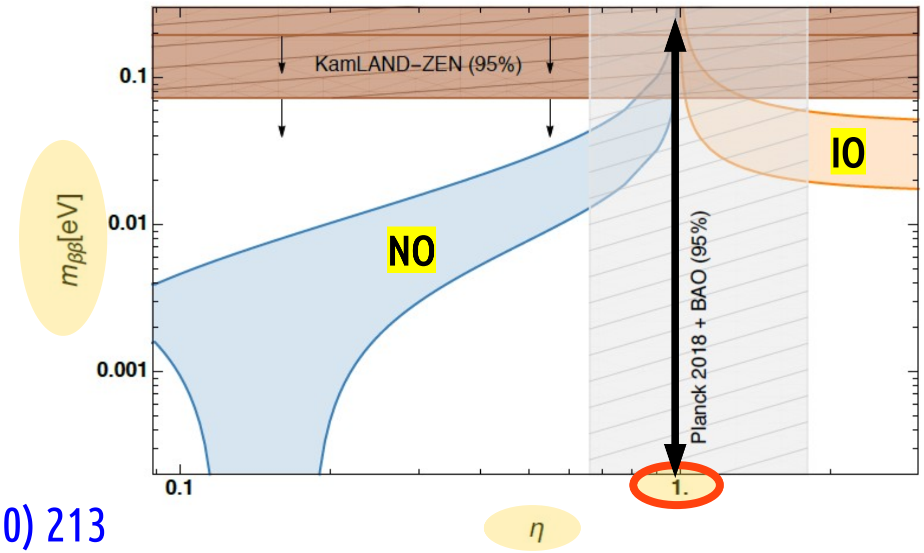
neutrinoless doublebeta decay

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

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

Nearly degenerate

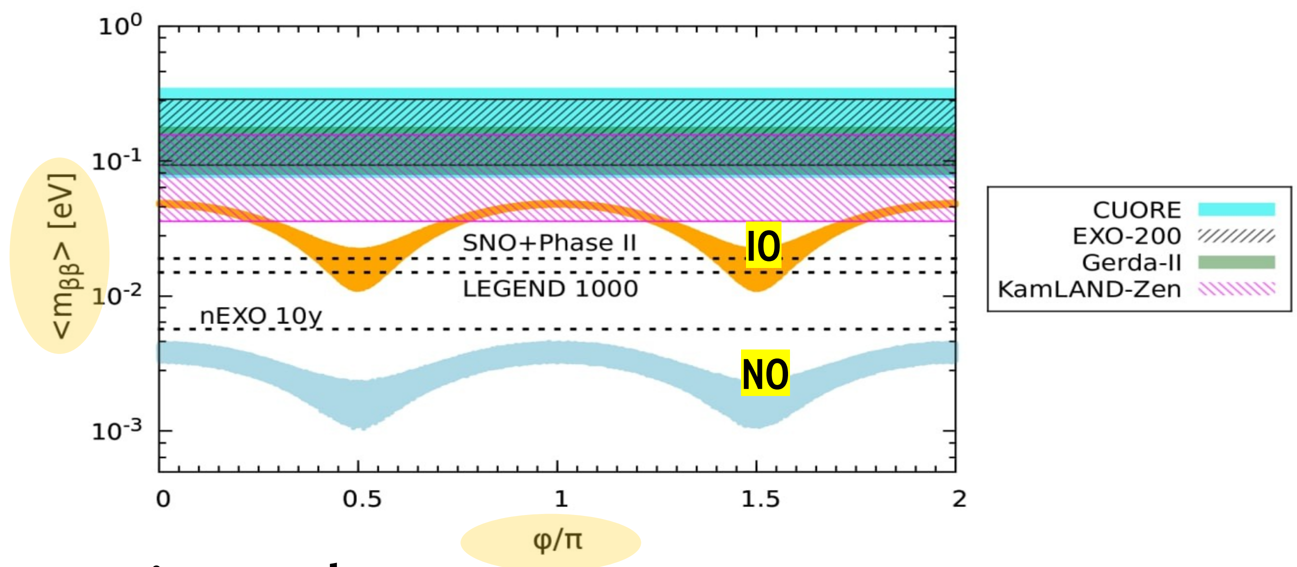
Lattanzi et al JHEP 10 (2020) 213



degeneracy parameter

- **One-massless neutrino**

Reig et al Phys.Lett. B790 (2019)303
Barreiros, Felipe & Joaquim JHEP (2019) 223
Mandal et al PLB789 (2019) 132
Avila et al Eur.Phys.J.C 80 (2020) 10, 908



majorana phase

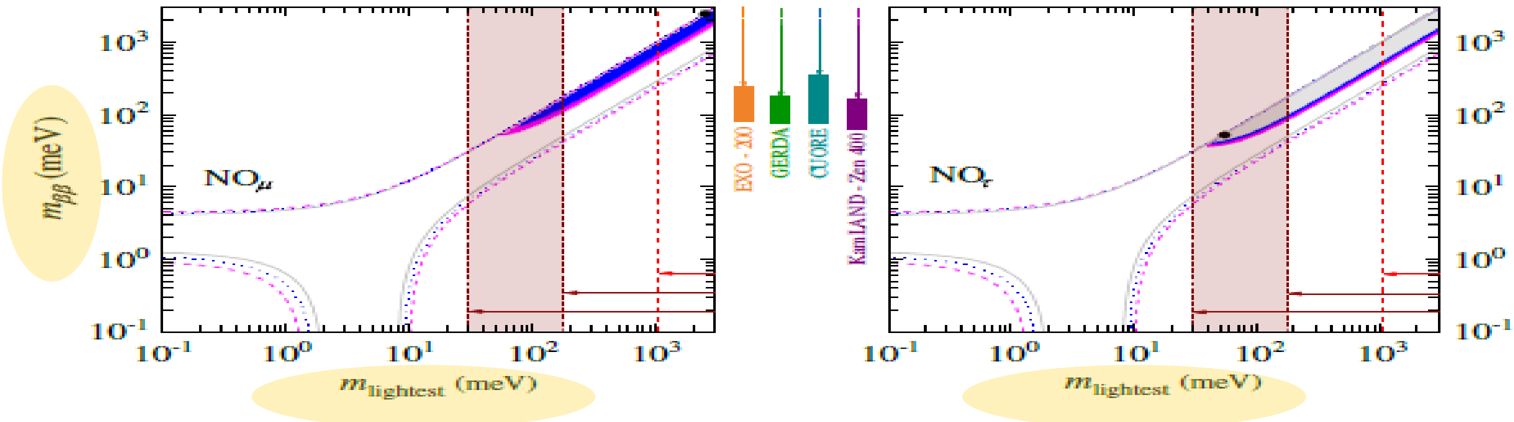
C Adams et al 2212.11099
Agostini et al. Science 365 (2019) 1445

➢ **3-massive case**

Lower bounds from family symmetries

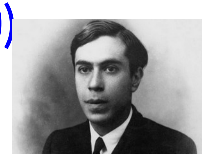
Dorame et al PhysRevD86(2012)056001
Dorame et al Nucl.Phys.B 861 (2012) 259-270
King et al Phys.Lett. B 724 (2013) 68-72 etc

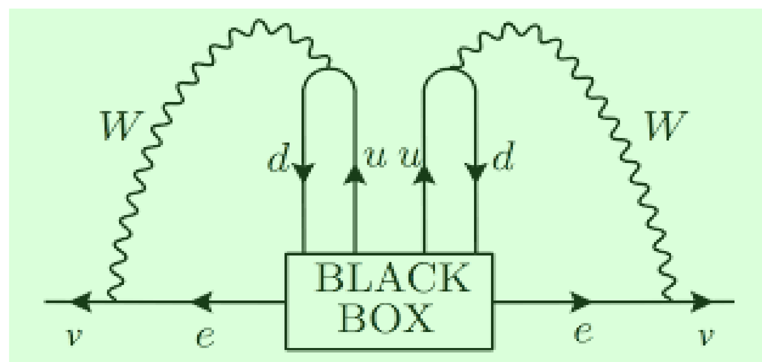
From Barreiros et al JHEP04(2021)249



Significance – the black box

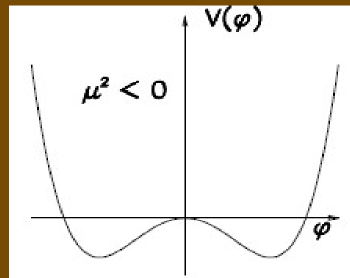
Schechter, Valle PhysRev D25 (1982) 2951
Duerr, Lindner, Merle JHEP06(2011)091
B.J.P. Jones 2108.09364 (TASI 2020)





Origin of neutrino mass

stability

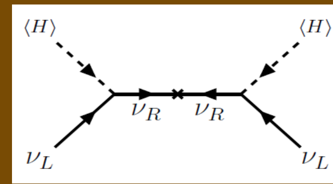


SEESAW dynamics

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

Mandal et al Phys.Rev.D 101 (2020) 115030

JHEP03(2021)212 & JHEP07(2021) 029



TYPE I

Minkowski 77

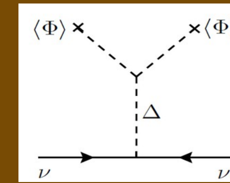
Gellman Ramond Slansky 80

Glashow, Yanagida 79

Mohapatra Senjanovic 80

Lazarides Shafi Weterrich 81

Schechter-Valle 80 & 82

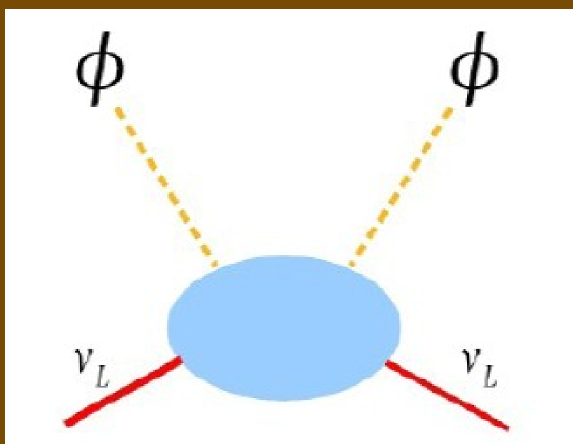


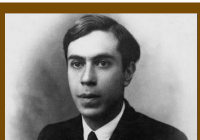
TYPE II

Schechter-Valle 80 & 82

L-R seesaw **# of Rs = # Ls**

SM seesaw **# of singlets arbitrary**

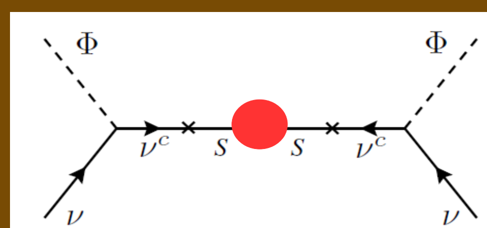




- **MISSING PARTNER**
  (3,2) min viable type1 seesaw
  (3,1) scoto-seesaw template

$m_{\beta\beta}$

- **LOW-SCALE Type1 SEESAW (3,6) ISS & LSS**

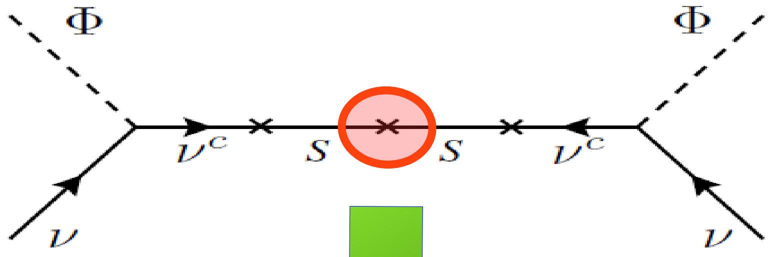


Mohapatra,Valle 86

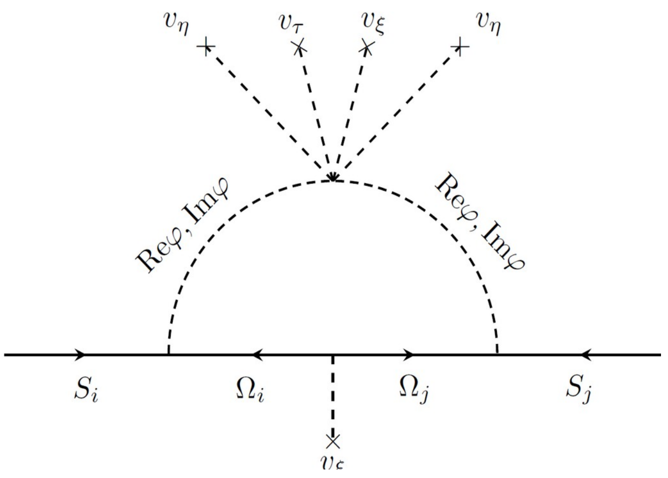
Akhmedov et al Phys.Rev.D53 (1996) 2752
PhysLettB368 (1996) 270

Malinsky et al PhysRevLett95(2005)161801

doubly protected inverse seesaw

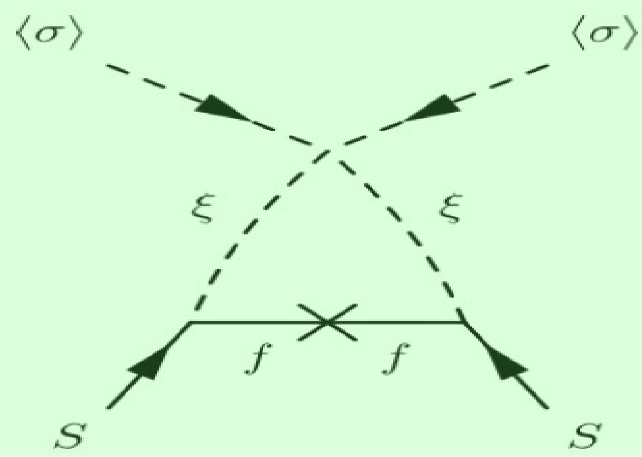


radiative inverse seesaw



L-R scheme

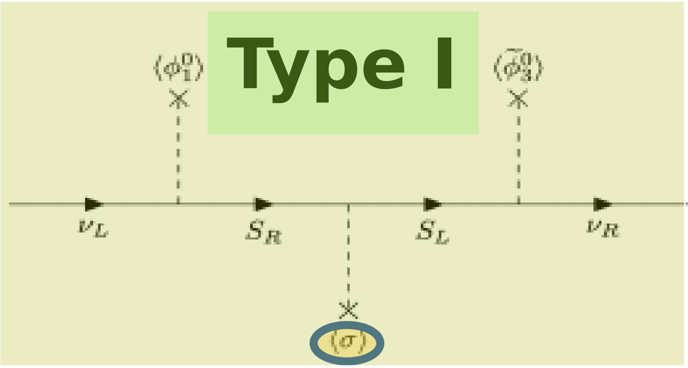
Cárcamo Hernández et al JHEP 1902 (2019) 065

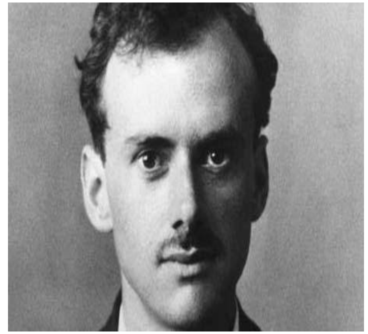


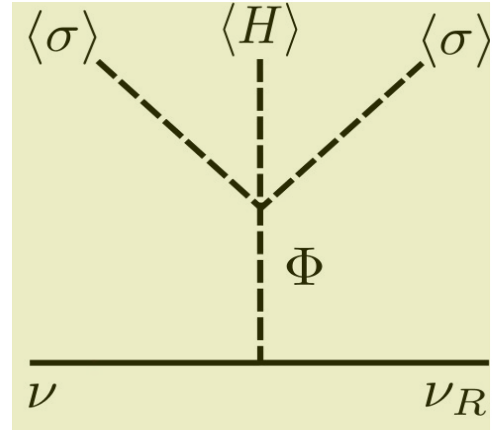
dark inverse seesaw

Mandal et al Phys.Lett.B821 (2021) 136609

Seesawing a la



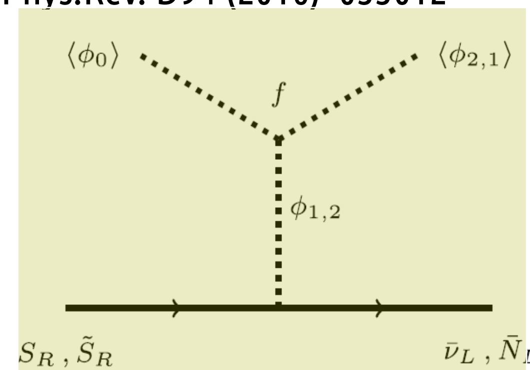




Type II

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



symmetry protecting small neutrino mass

+ Diracness

Peccei-Quinn symmetry

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

SU3L (w)

PQ (v_σ)

Phys.Lett.B 810 (2020) 135829

Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

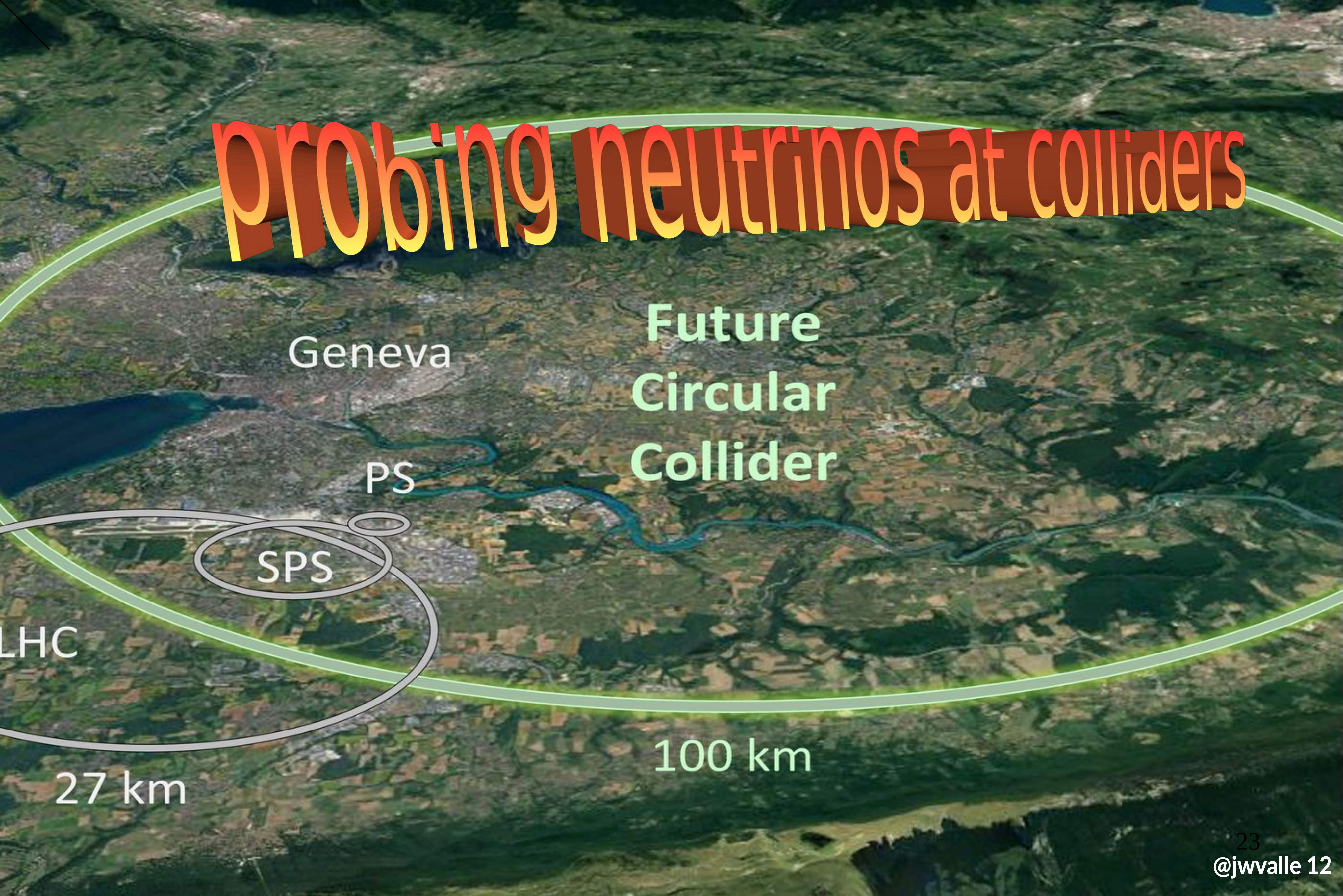
Phys.Rev. D98 (2018) 035009

Phys.Lett. B781 (2018) 122-128

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

Phys.Lett. B755 (2016) 363-366

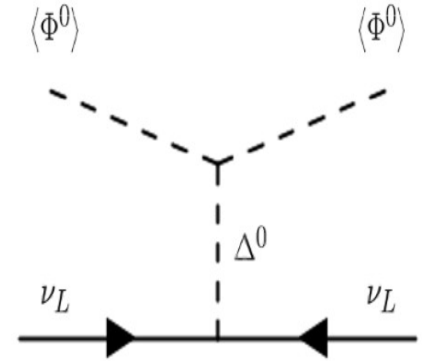
probing neutrinos at colliders



simplest seesaw

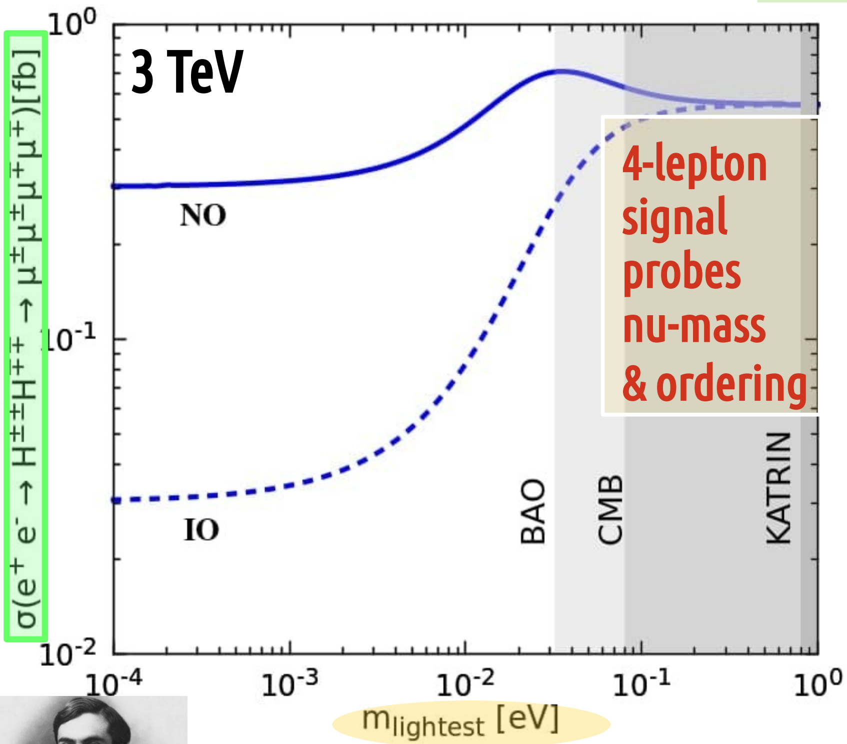
current oscillation data can reconstruct triplet seesaw so that it can be tested at high-energies

Schechter & JV PRD22 (1980) 2227
PRD25 (1982) 774

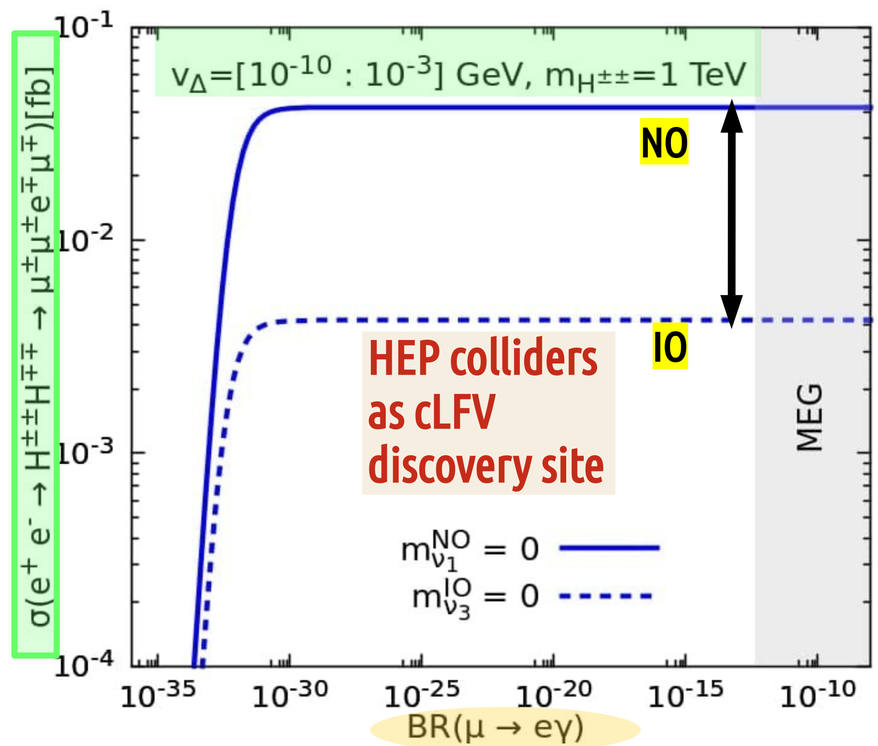


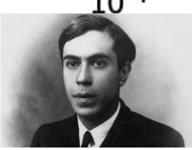
seesaw mediator produced in @ e+e- / pp collisions

Miranda et al Phys.Rev.D105 (2022) 095020



Miranda et al PLB 829 (2022) 137110





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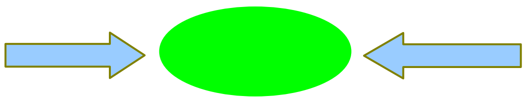
PROBING NEUTRINO PROPERTIES AT COLLIDERS

LSP from cascade squark & gluino decays

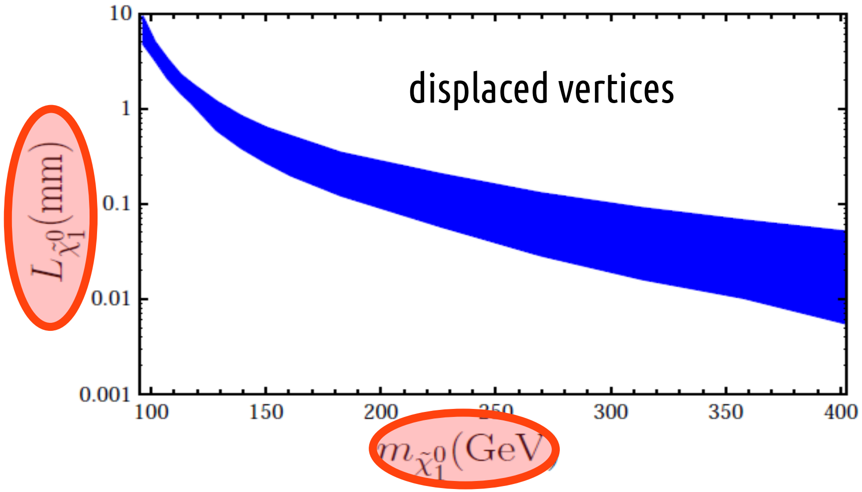
De Campos et al
Phys.Rev. D86 (2012) 075001

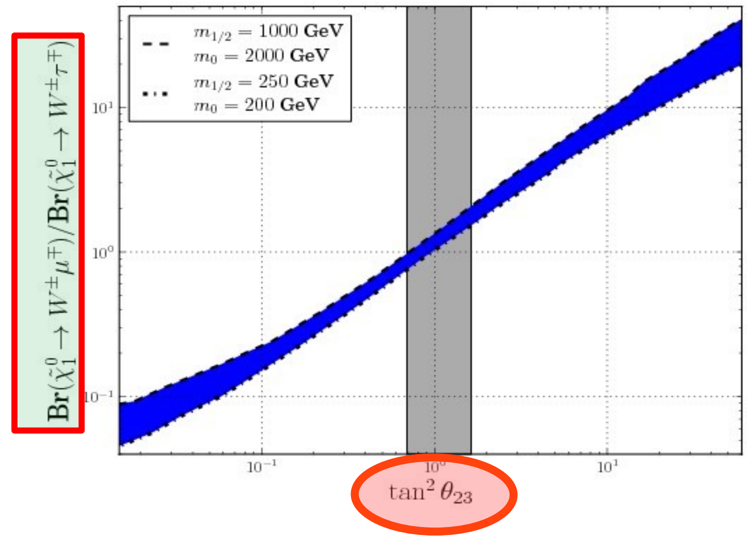
$$\tilde{\chi}_1^0 \to W^{\pm} l_i^{\mp} \qquad \tilde{\chi}_1^0 \to Z^0 \nu_i$$



Lightest neutralino decay correlates with atm angle

Lightest neutralino decay length

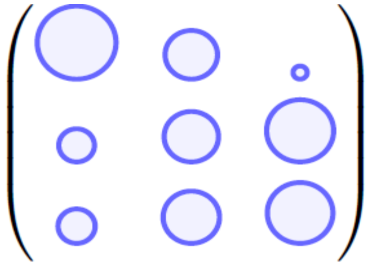




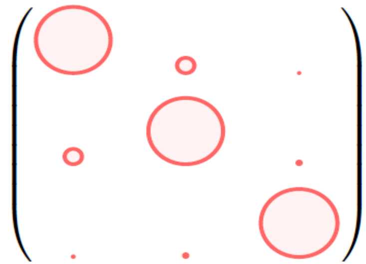
PROBING **Theta_atm** @ **LHC**

flavour legacy of oscillations

Q/L mixing pattern



versus



Q/L mass hierarchies

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

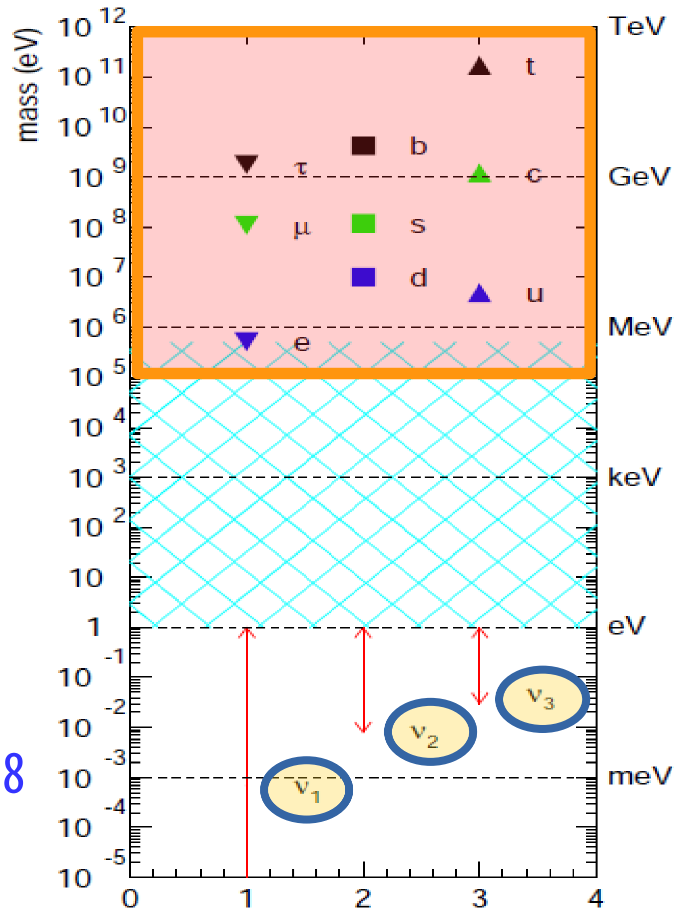
Morisi et al Phys.Rev. D84 (2011) 036003

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

Reig, JV, Wilczek Phys.Rev. D98 (2018) 095008



a more radical departure??

@jwvalle 15

Higgs discovery is not the last brick !

Oscillation discovery brought neutrinos to the spotlight

Precision oscillation program, CP, octant, ordering, NSI, unitarity, 0nuDBD, **CEvNS** ...

Collider imprints of neutrino completions:

cLFV signatures from seesaw mediators

neutrinos and flavor

neutrinos and dark matter

neutrinos and strong CP problem

neutrinos and unification

neutrinos and SM anomalies

Back-ups

Phys.Lett. B199 (1987) 432
Nucl.Phys. B908 (2016) 436
Phys.Rev. D92 (2015) 053009
New J. Phys. 19 (2017) 093005

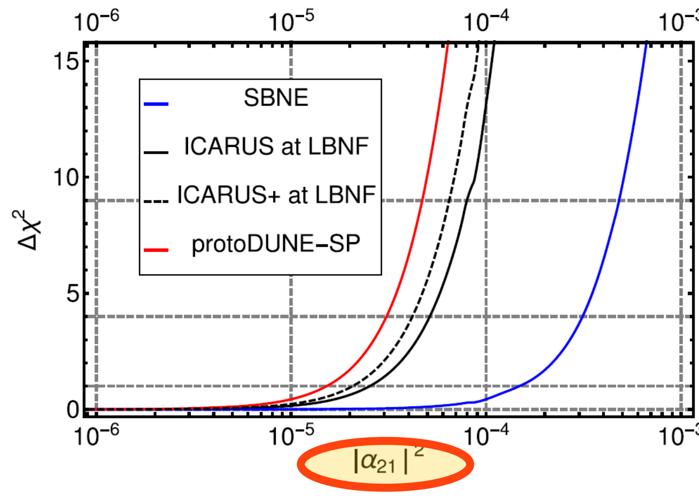
robustness

unitarity test

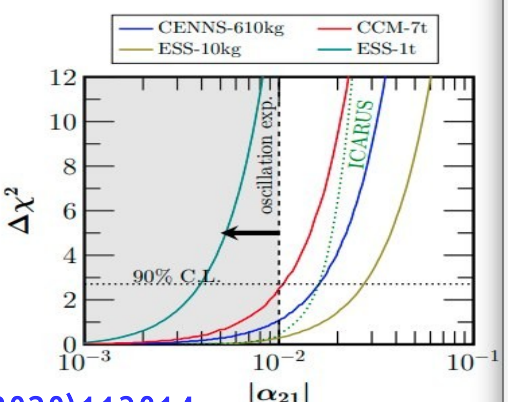
$$\begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

near measurements needed
Shao-Feng Ge et al
Phys.Rev. D95 (2017) 033005

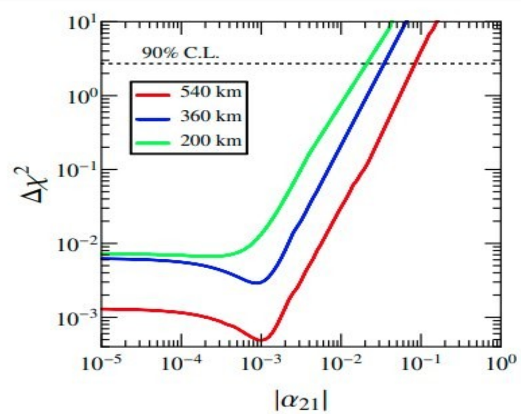
	One parameter (1 d.o.f.)		All parameters (6 d.o.f.)	
	90% C.L.	3σ	90% C.L.	3σ
	Neutrinos only			
$\alpha_{11}>$	0.98	0.95	0.96	0.93
$\alpha_{22}>$	0.99	0.96	0.97	0.95
$\alpha_{33}>$	0.93	0.76	0.79	0.61
$\|\alpha_{21}\|<$	1.0×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	3.6×10^{-2}
$\|\alpha_{31}\|<$	4.2×10^{-2}	9.8×10^{-2}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



PRD97 (2018) 095026

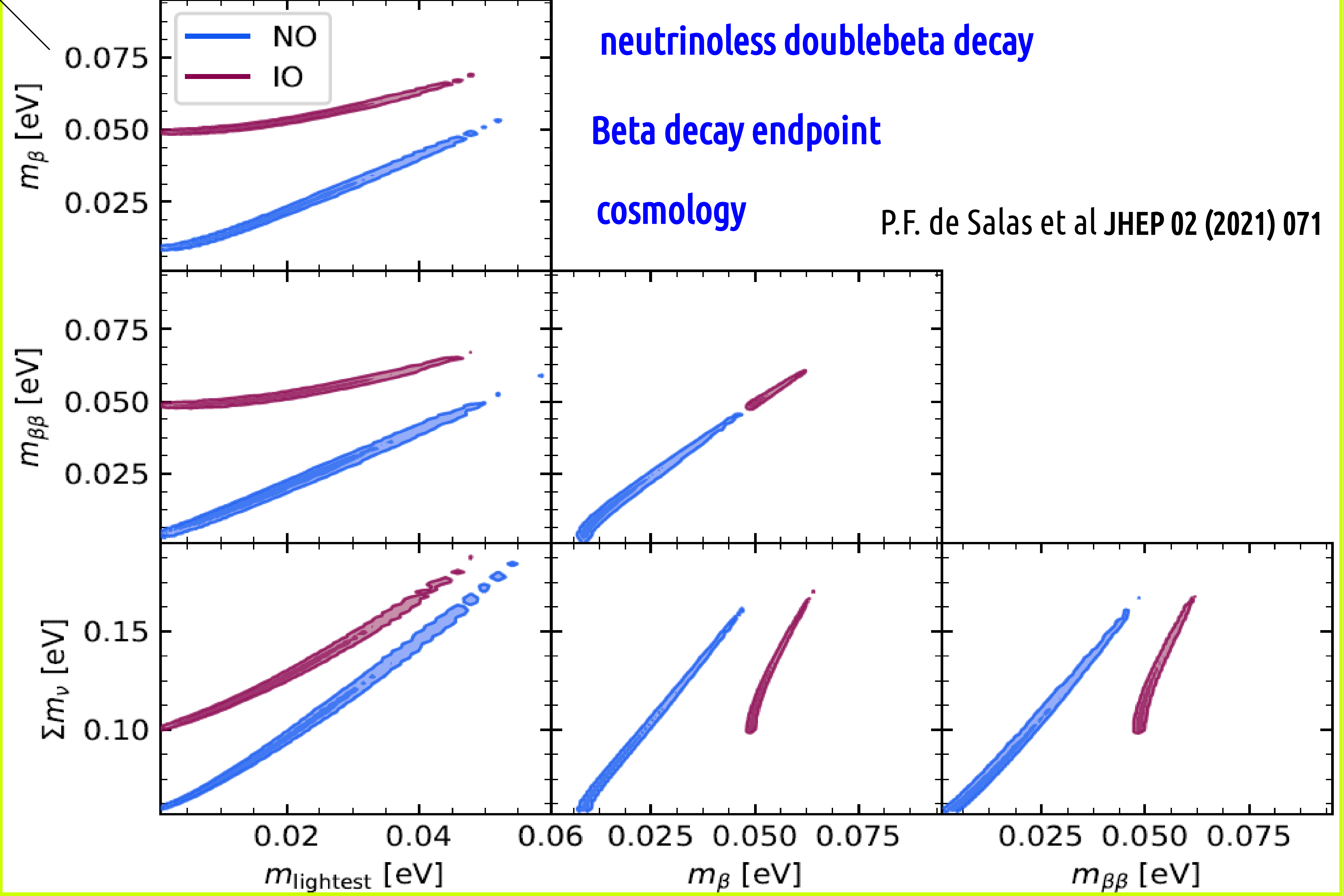


PhysRevD102(2020)113014



ESSnuB

PRD106(2022)07501



neutrinoless doublebeta decay

Beta decay endpoint

cosmology

P.F. de Salas et al **JHEP 02 (2021) 071**

5D warped flavordynamics predictions

Randall-Sundrum Phys.Rev.Lett. 83 (1999) 3370

- **mass hierarchies from geometry**

Arkani-Hamed & Schmaltz hep-ph/9903417

- **mixing angles from family symmetry**

TM mixing pattern predicted from T'

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

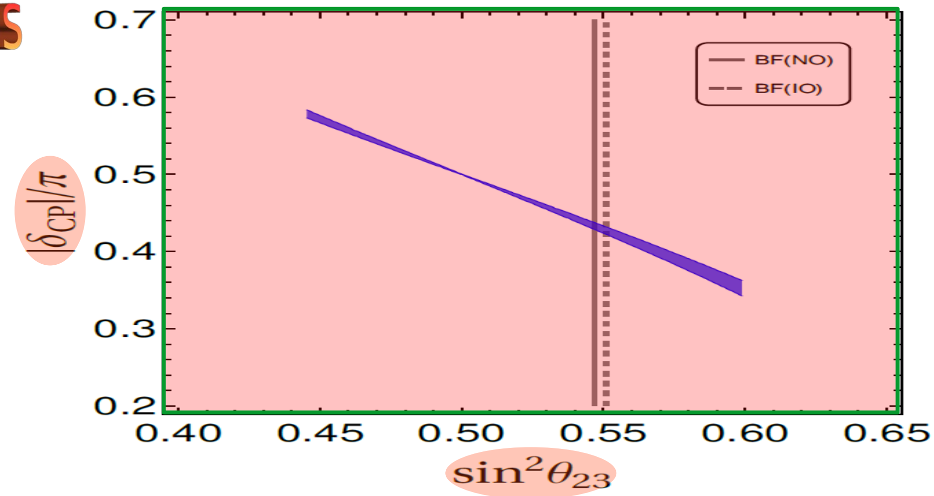
TM1 pattern

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

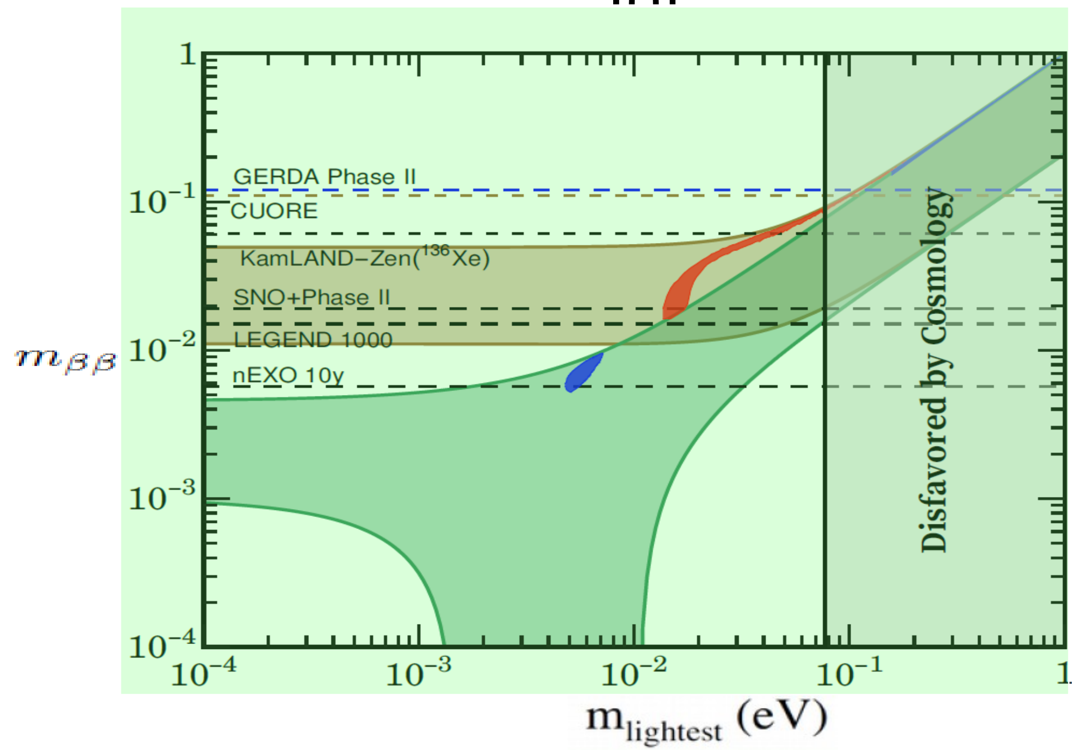
Chen et al Phys. Rev. D 102, 095014 (2020)

TM2 pattern

Dirac neutrino alternative
Chen et al JHEP01(2016)007
Phys. Rev. D95 (2017) 095030
Phys.Lett. B771 (2017) 524



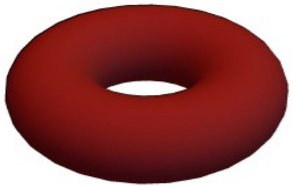
TM1



6D Orbifold flavor predictions

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

Phys.Lett.B 801 (2020) 135195
Phys.Rev.D 101 (2020) 11, 116012

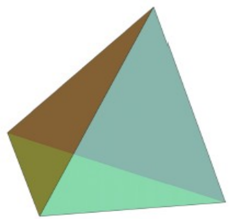


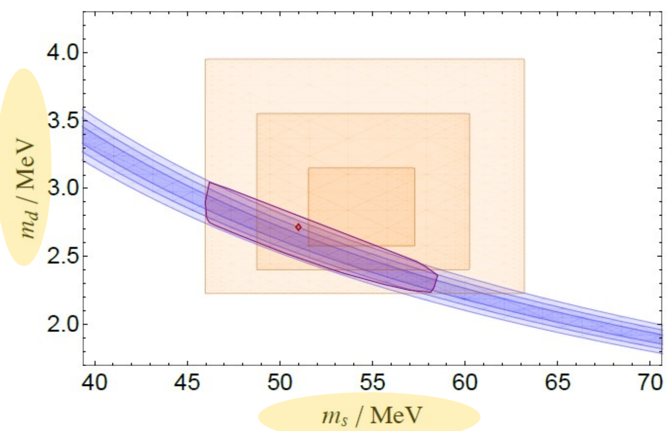
A4 family symmetry “derived”

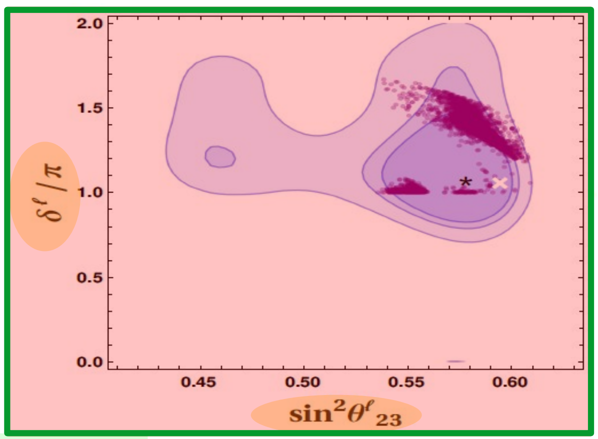
Phys.Rev.D 105 (2022) 055030

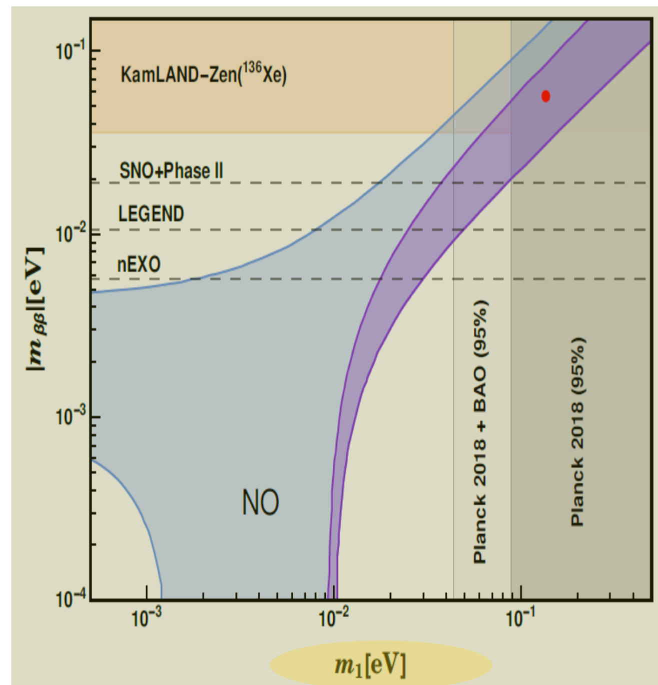
Golden Q-L relation

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

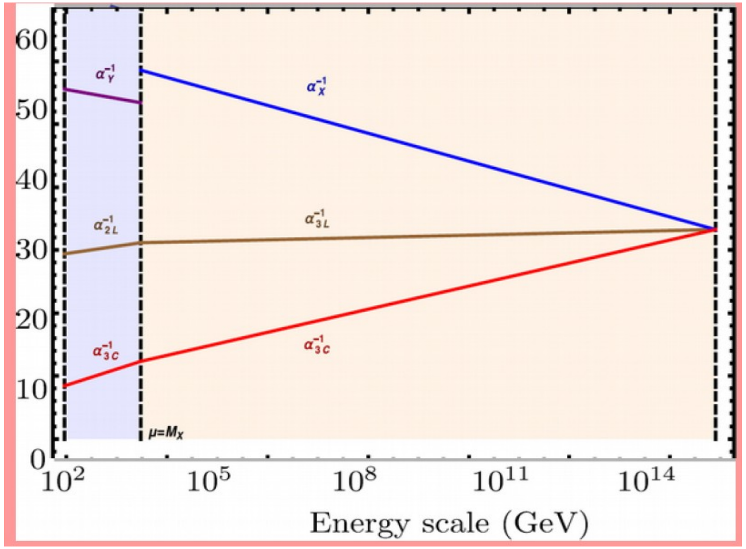








Good global fit of flavor observables



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

neutrino path to unification

why 3 families

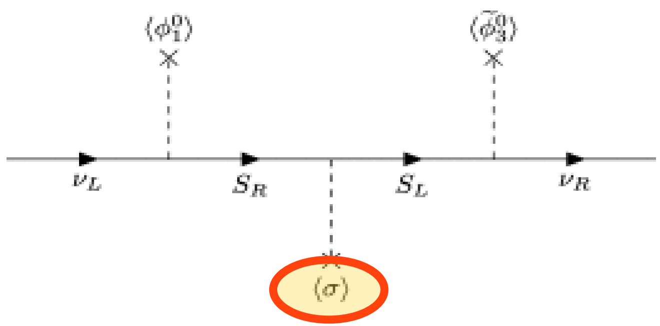
Boucenna et al Phys. Rev. D 91, 031702 (2015)

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

Old 331 model

PRD22(1980)738

Dirac seesaw



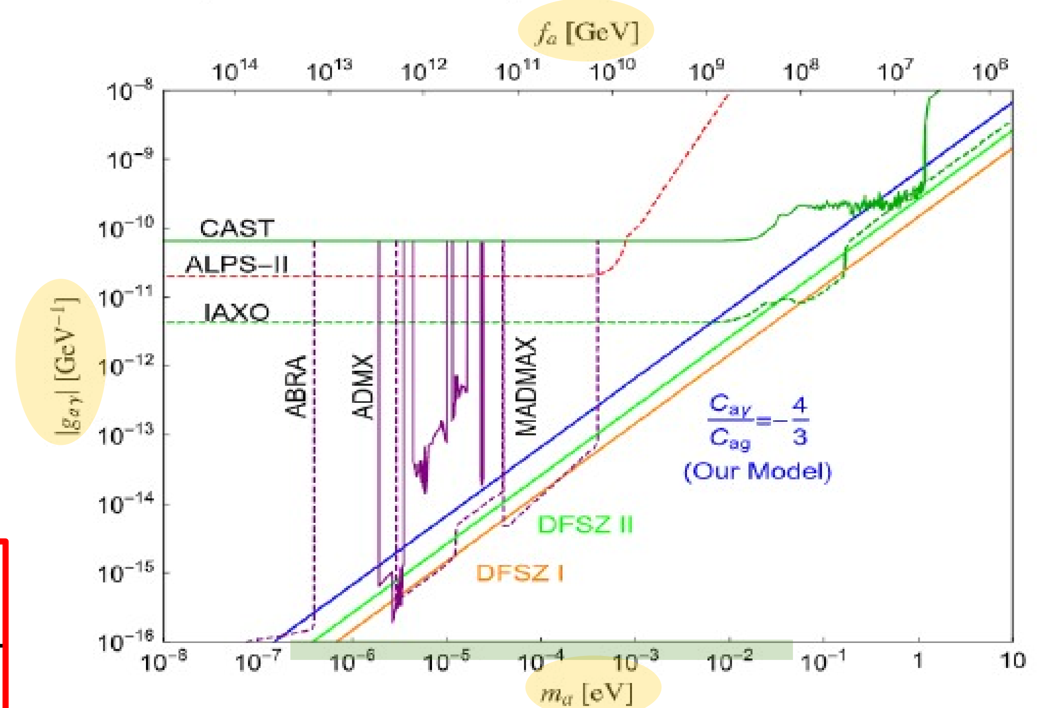
from Peccei-Quinn symmetry

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

SU3L

PQ

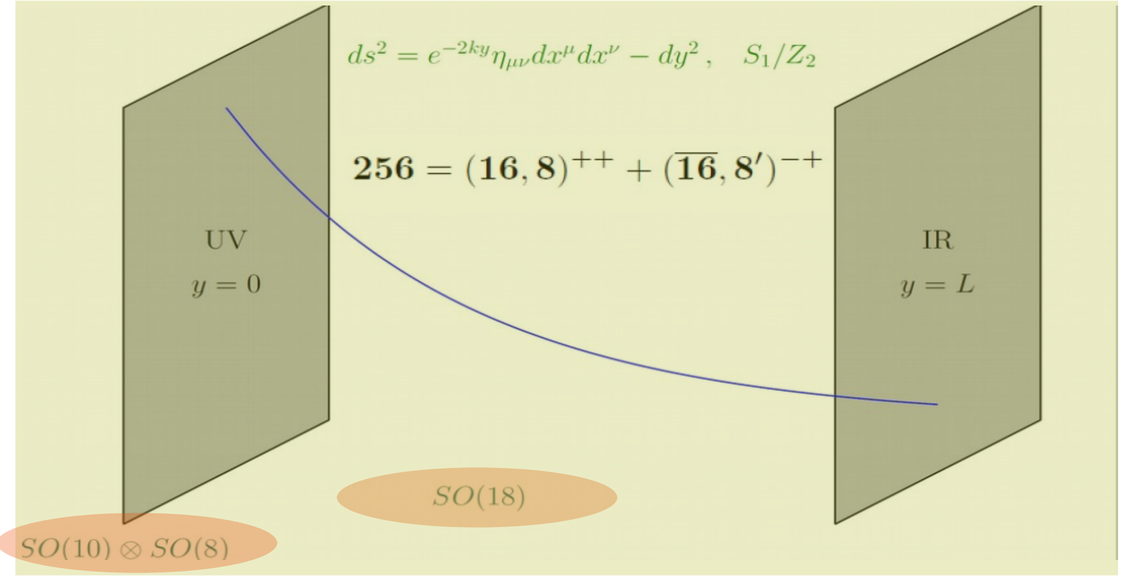
Physics Letters B 810 (2020) 135829



tree-level quark FCNC

new path to family unification

inspired by beauty of neutrinos in SO10



Reig, Valle, Vaquera-Araujo, Wilczek
PLB774 (2017) 667-670

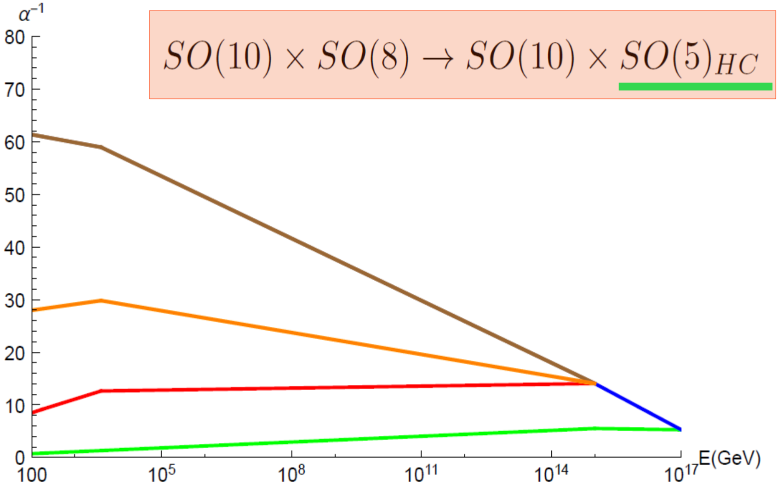
use orbifold BC to decouple mirrors

unwanted chiral families bound by new hypercolor force above TeV

new spectroscopy

promote M4 to AdS5

Reig, JV, Wilczek
Phys.Rev. D98 (2018) 095008



- **viable SO3 family symmetry**
- **golden Q-L mass formula**
- **PQ symmetry & axion**

CDFII W mass anomaly

$$m_W^{\rm CDF} = 80.4335 \pm 0.0094 \ \text{GeV}$$

$$m_W^{\rm SM} = 80.354 \pm 0.007 \ \text{GeV}$$

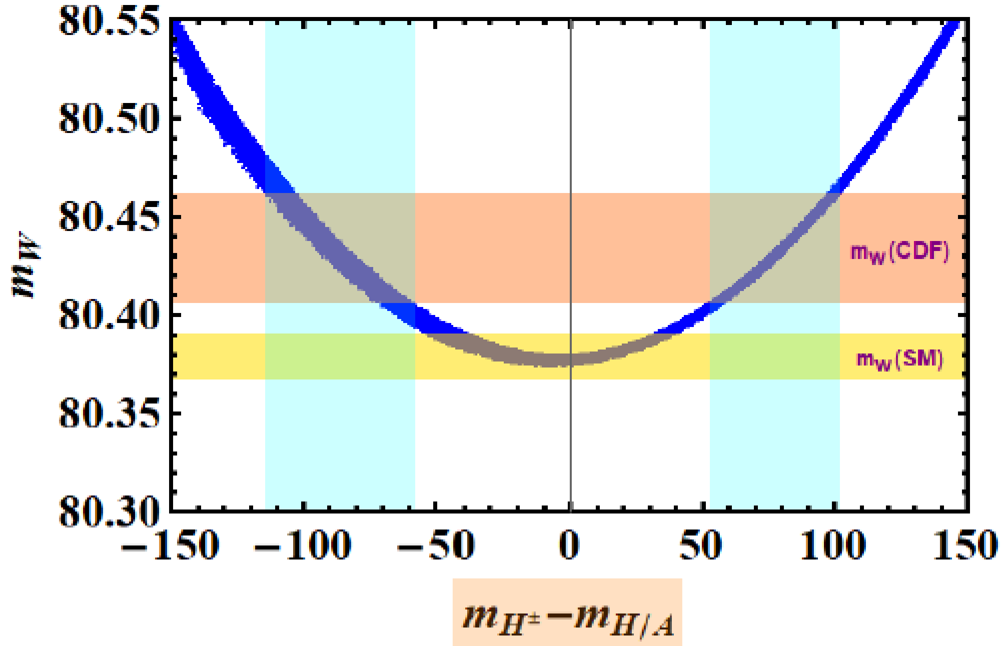
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M_R \\ M_L^T & M_R^T & 0 \end{pmatrix}$$

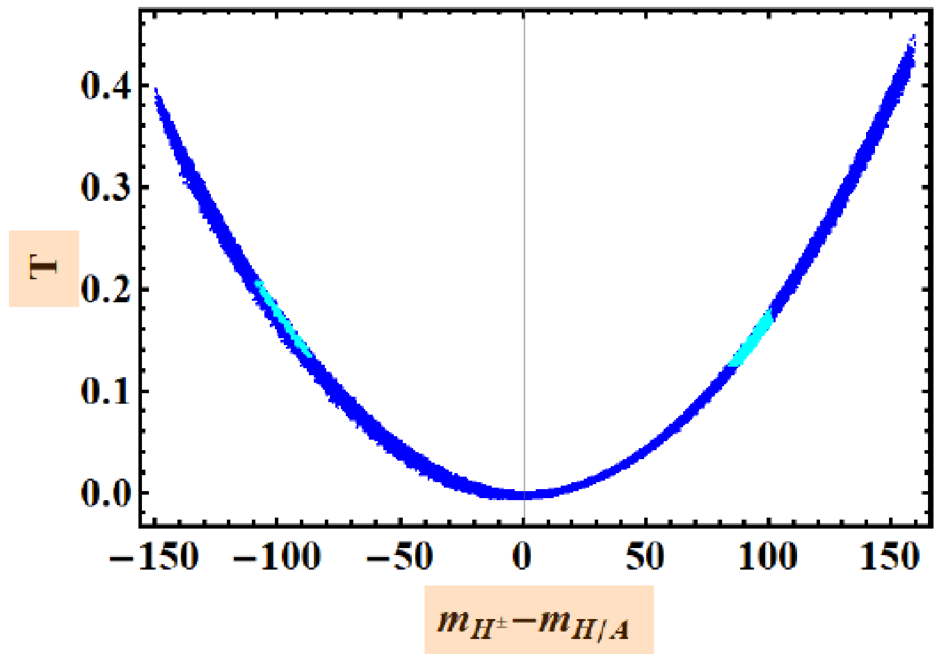
$$m_W^2 = m_W^2\big|_{\rm SM}\left(1 + \frac{s_W^2}{c_W^2 - s_W^2}\,\Delta r|_{\rm NP}\right)$$

$$\frac{\alpha}{s_W^2}\left(-\frac{1}{2}S + c_W^2\,T + \frac{c_W^2 - s_W^2}{4 s_W^2}\,U\right)$$

Phys.Lett.B 834 (2022) 137408

all 1sigma, except for CDF band, which is 3

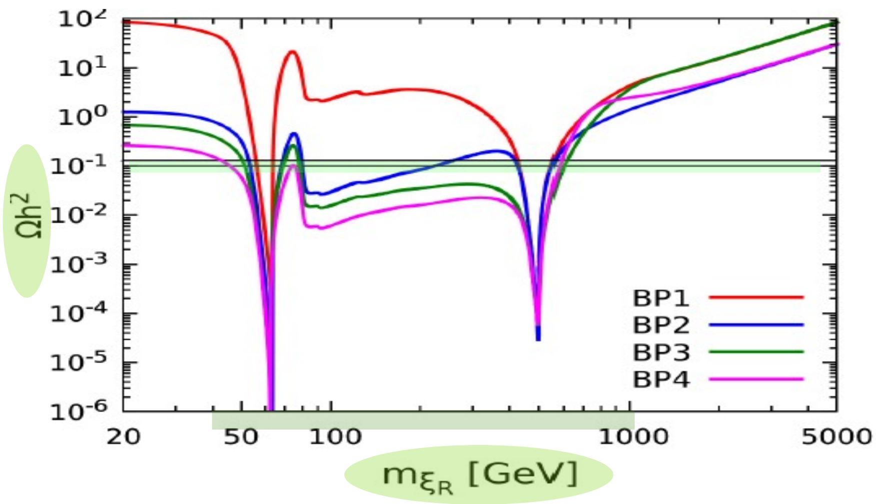




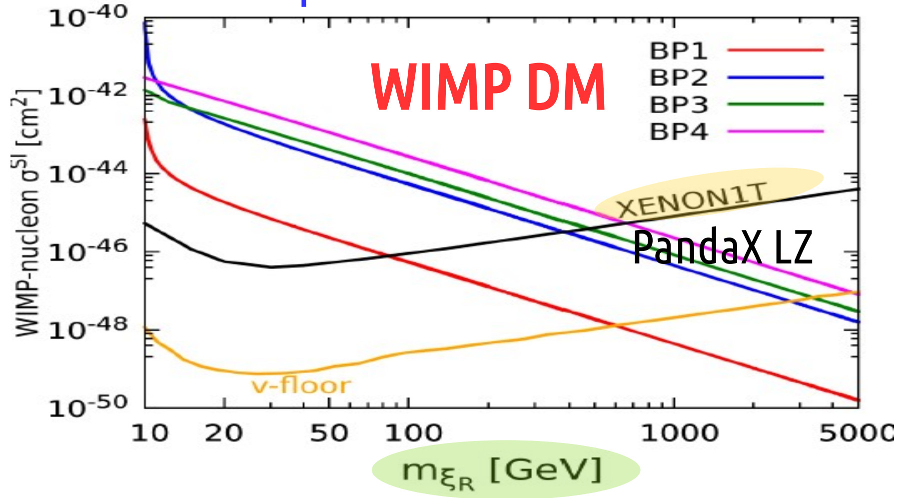
dark inverse typeI seesaw mechanism

LambdaCDM

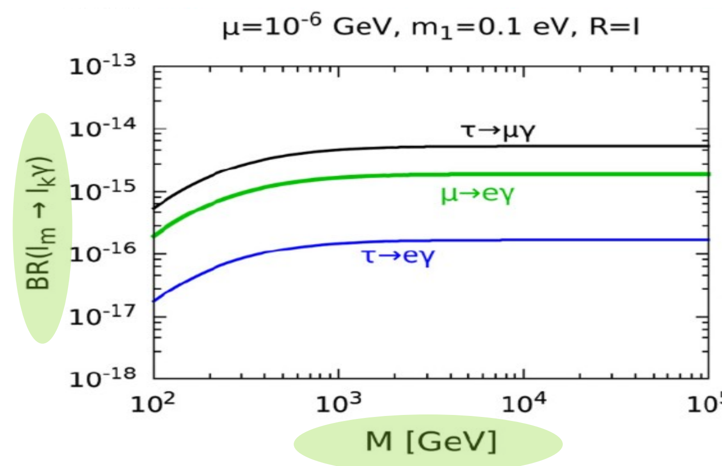
Phys.Lett.B 821 (2021) 136609

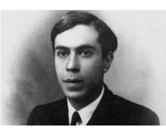


Xenon1T PhysRevLett.121.111302
PandaX Lux-Zepellin



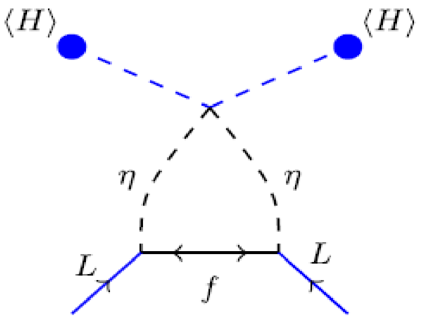
e.g. large cLFV from inverse type I seesaw
Mandal et al
Phys.Lett.B 821 (2021) 136609
(larger values possible)





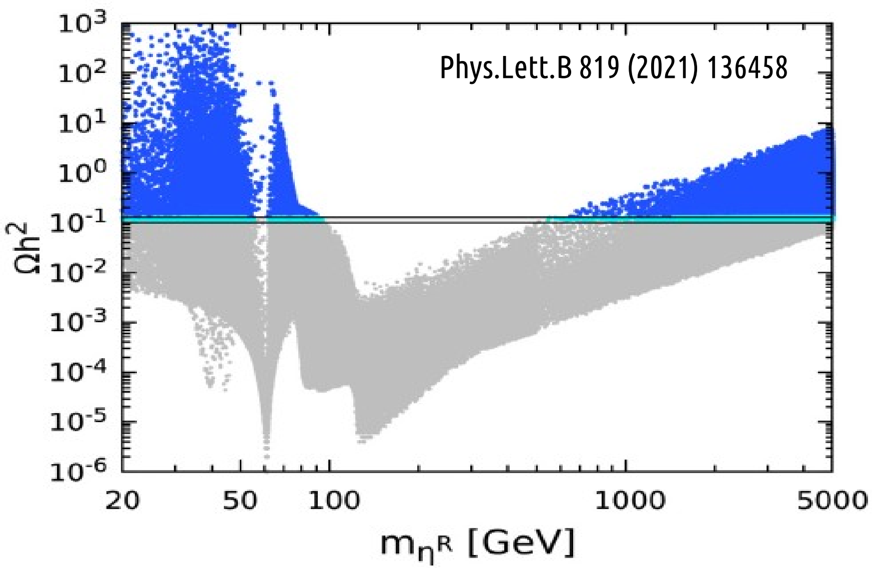
scotoseesaw : combining WIMP & seesaw paradigms

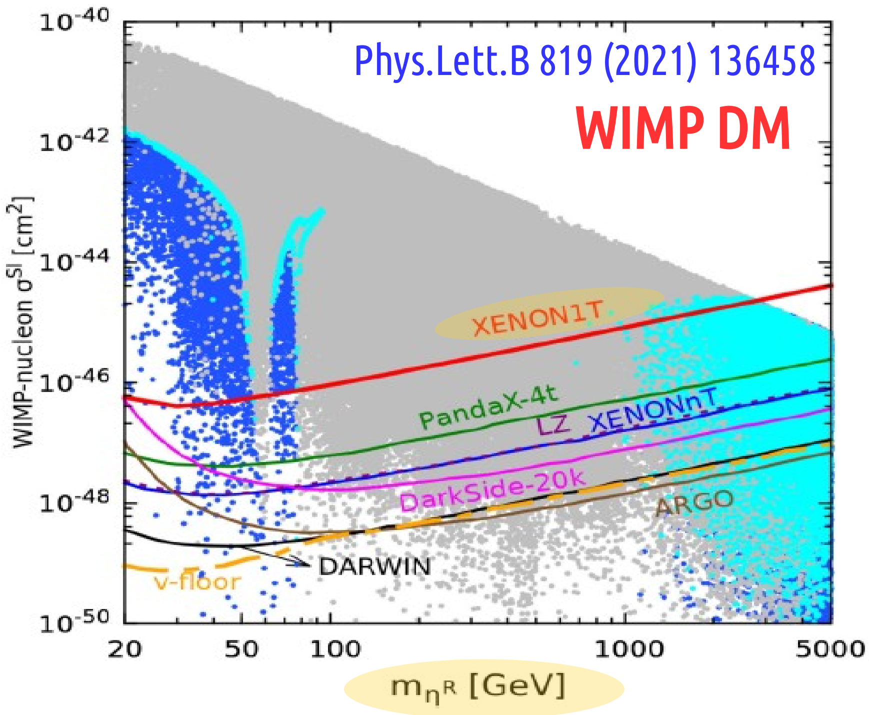
Loop solar scale

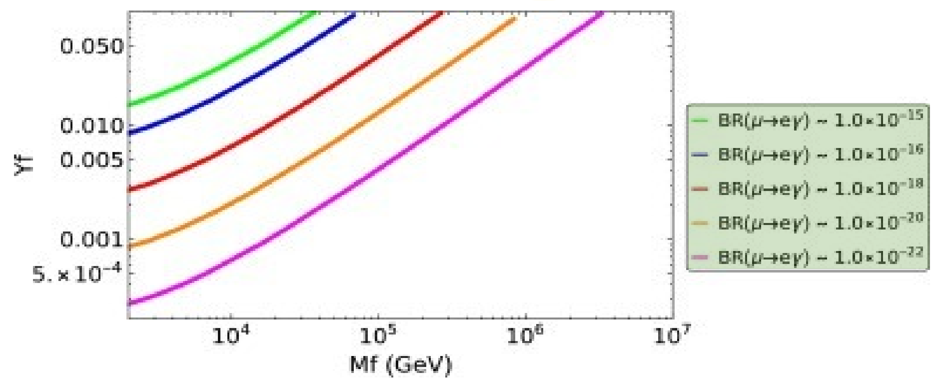


$$\Delta m^2_{\rm ATM} = \left(\frac{v^2}{2M_N}\mathbb{Y}_N^2\right)^2 , \quad \Delta m^2_{\rm SOL} \approx \left(\frac{1}{32\pi^2}\right)^2 \left(\frac{\lambda_5 v^2}{M_f^2 - m_\eta^2} M_f \mathbb{Y}_f^2\right)^2$$

Tree atm scale from type-I seesaw







$0\nu\beta\beta$ lower bound

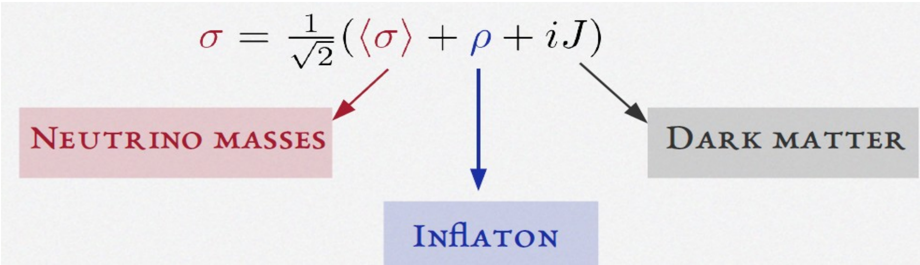
cLFV from "dark" loops

majoron dark matter

DM Berezinsky, Valle PLB318 (1993) 360

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

LG Aristizabal et al JCAP 1407 (2014) 052



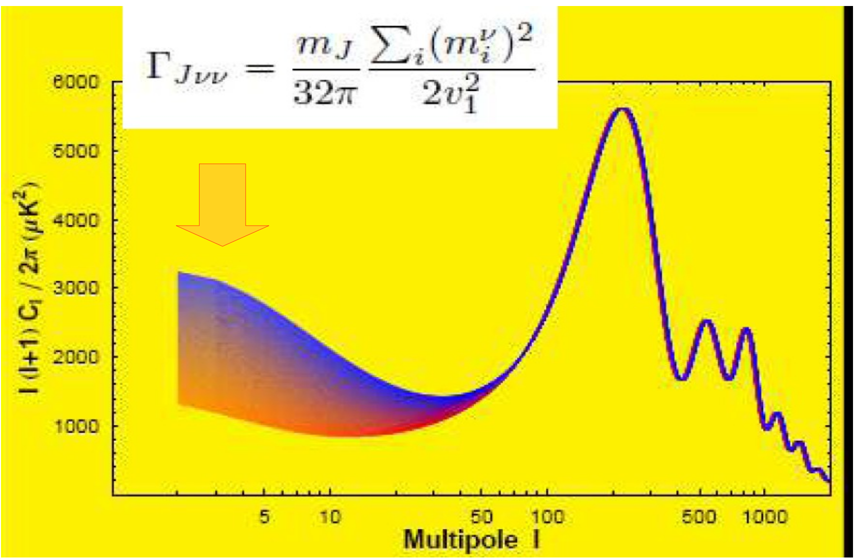
X-rays from DM decay

$J \to \gamma\gamma$

Lattanzi et al PRD88 (2013) 063528

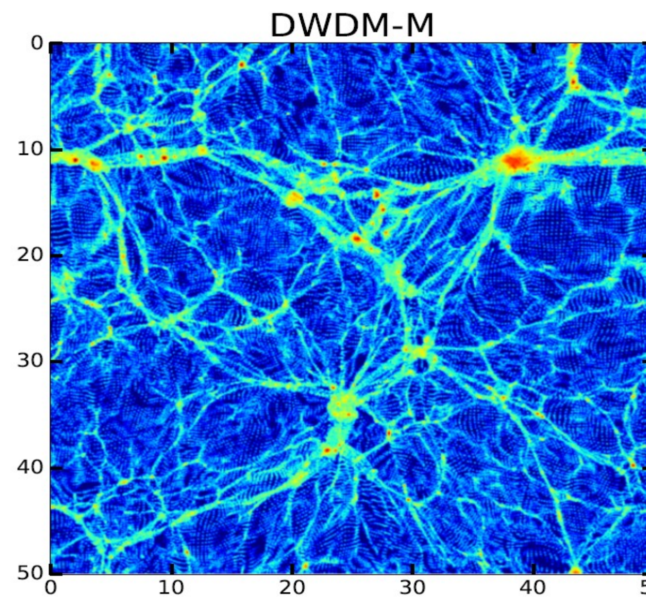
Consistency with CMB

Lattanzi & Valle, PRL99 (2007) 121301



large scale structure

Kuo et al JCAP 1812 (2018) 026



Light majoron CDM Reig, Yamada, JV JCAP09 (2019) 029