neutrino pathways to new physics

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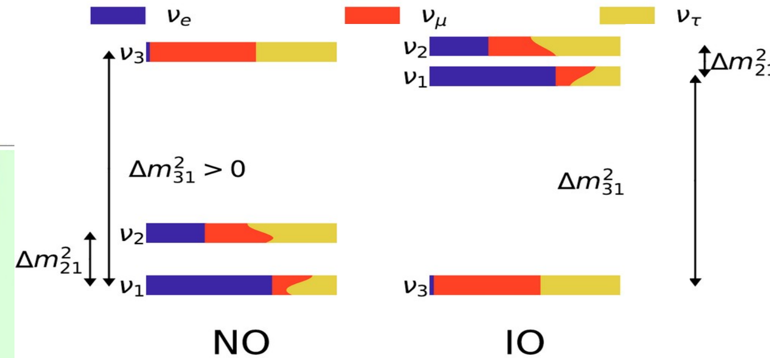
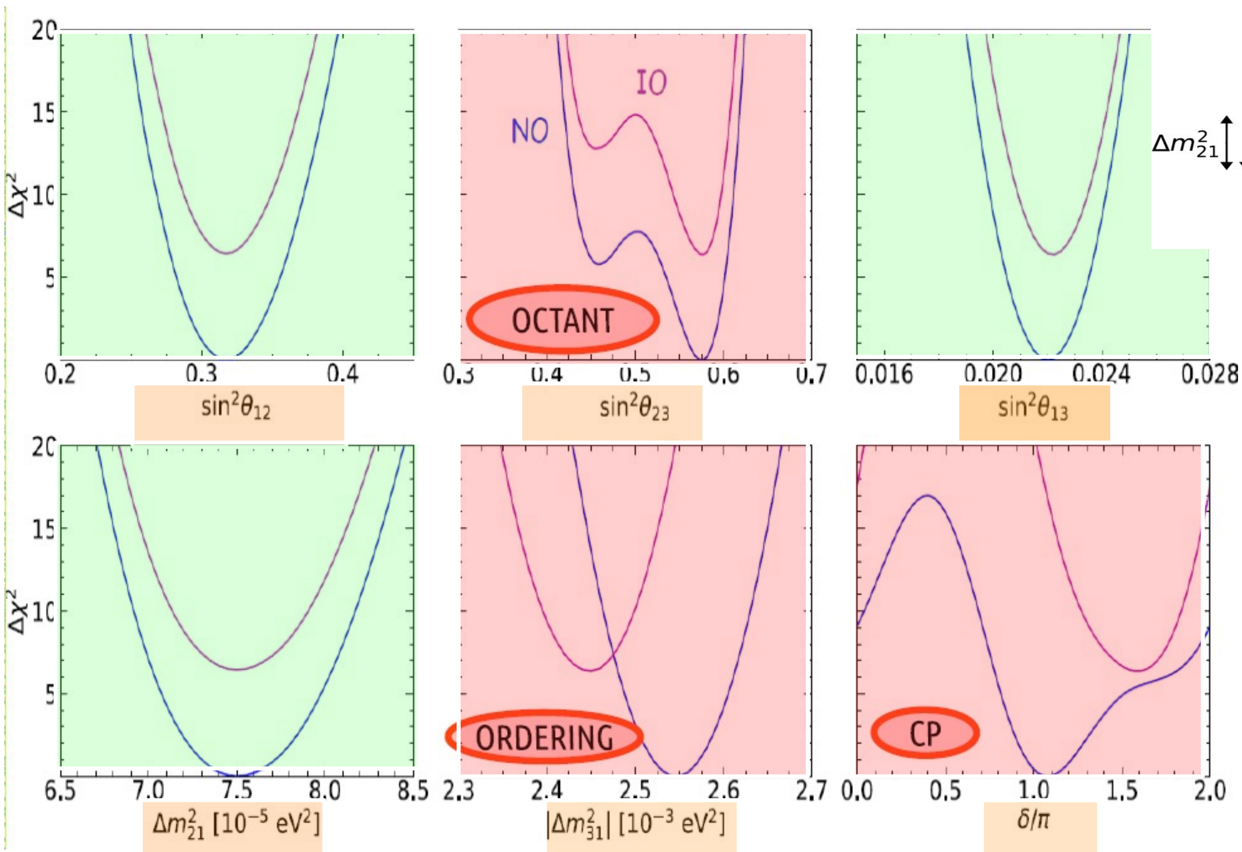
GENERALITAT VALENCIANA Conselleria d'Educació, Investigació, Cultura i Esport

neutrino oscillations

PF de Salas et al JHEP02(2021)071

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





Similar results from Bari and NuFit groups

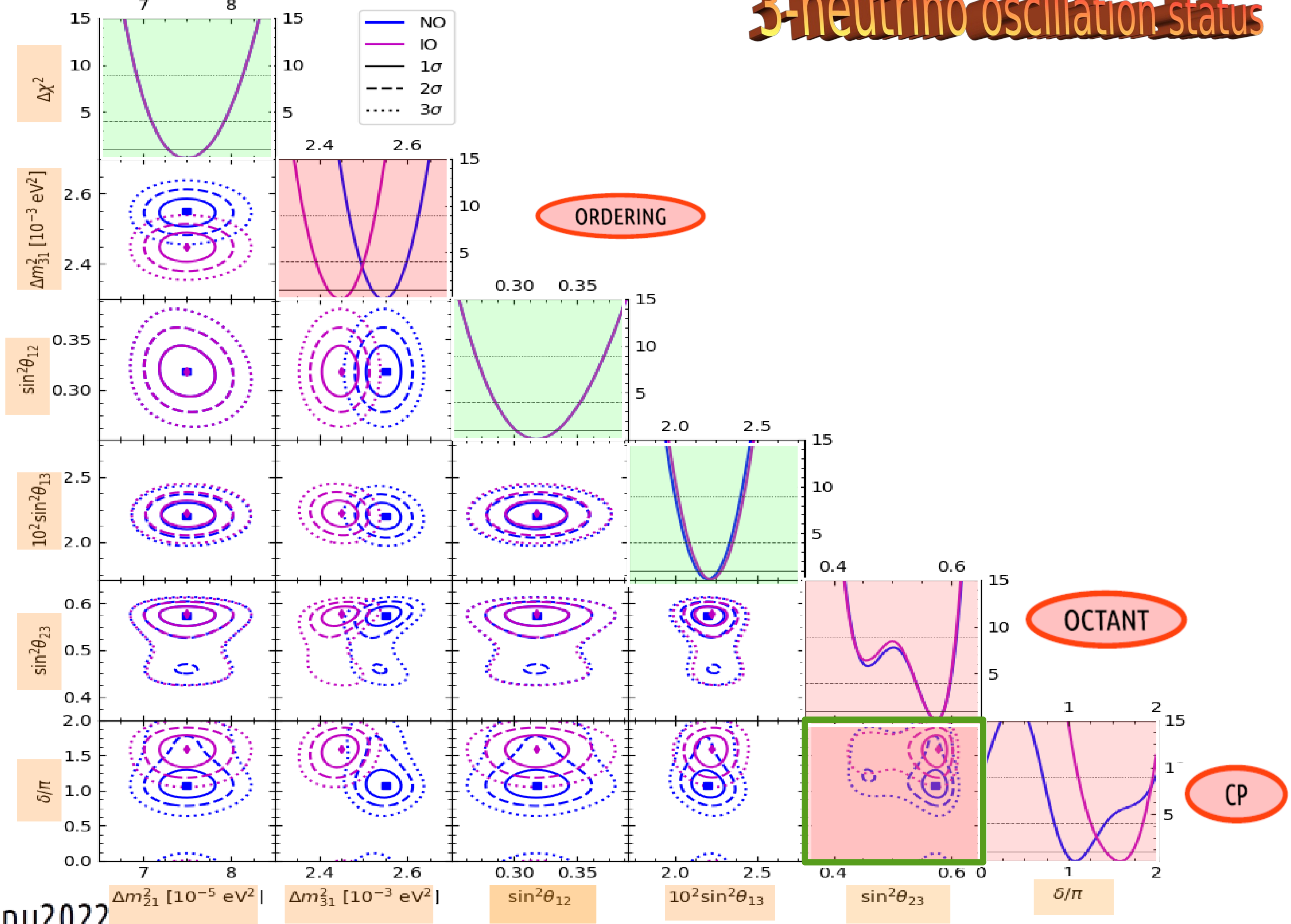
@jwvalle2

3-neutrino oscillation status

PF de Salas et al JHEP02(2021)071

https://globalfit.astroparticles.es/

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



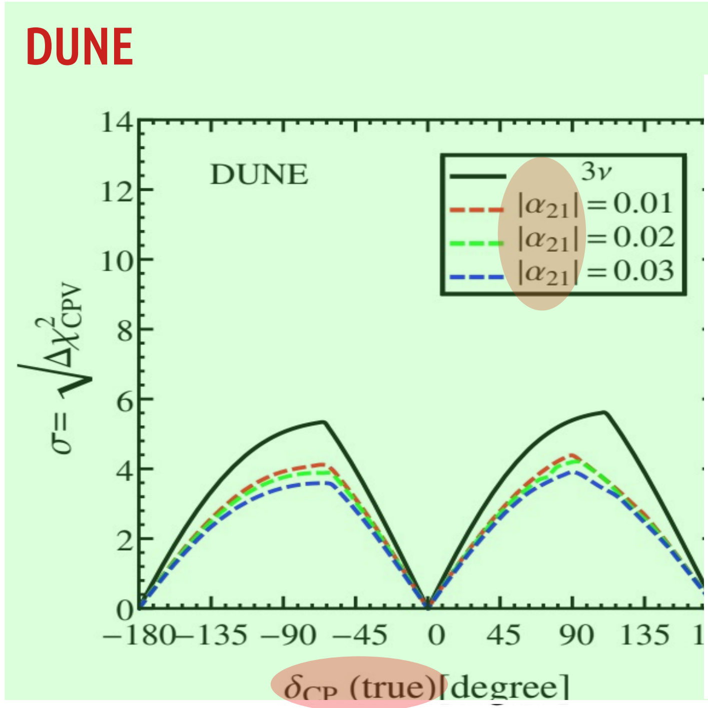
Updates from nu2022

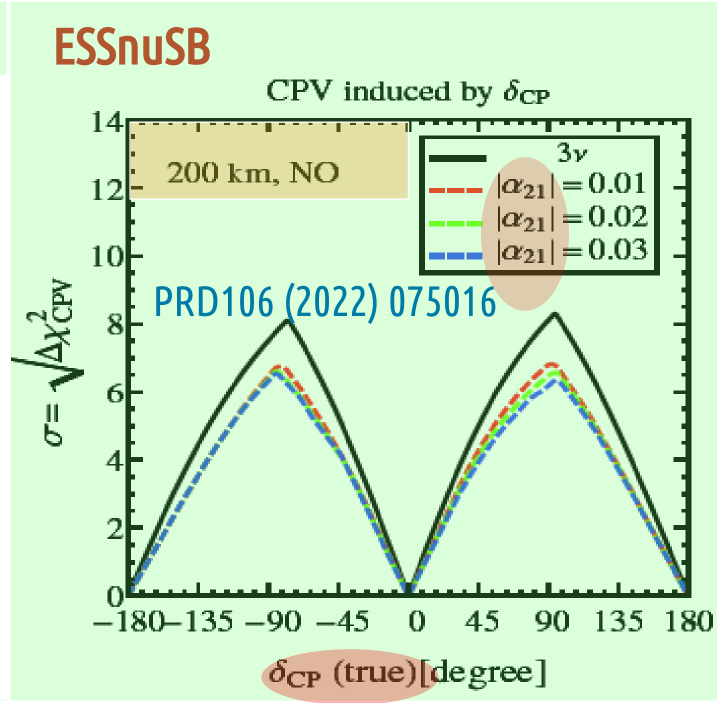
$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024} \quad \text{(2.8\% precision)}$$

@jwvalle3

CPV

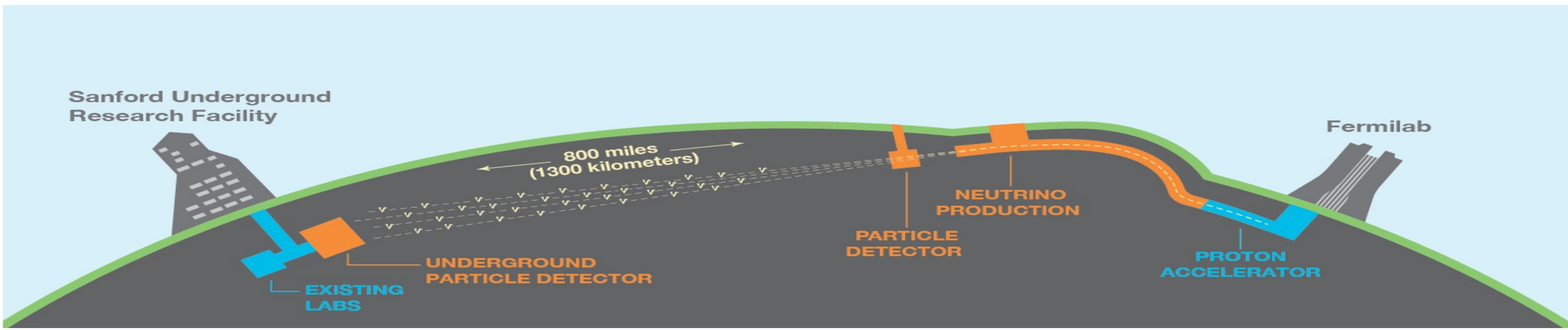
PhysRevLett117(2016)061804
New J.Phys. 19 (2017) 9, 093005
PhysRevD97 (2018) 095026
2008.12769





DUNE
Hyper-K

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

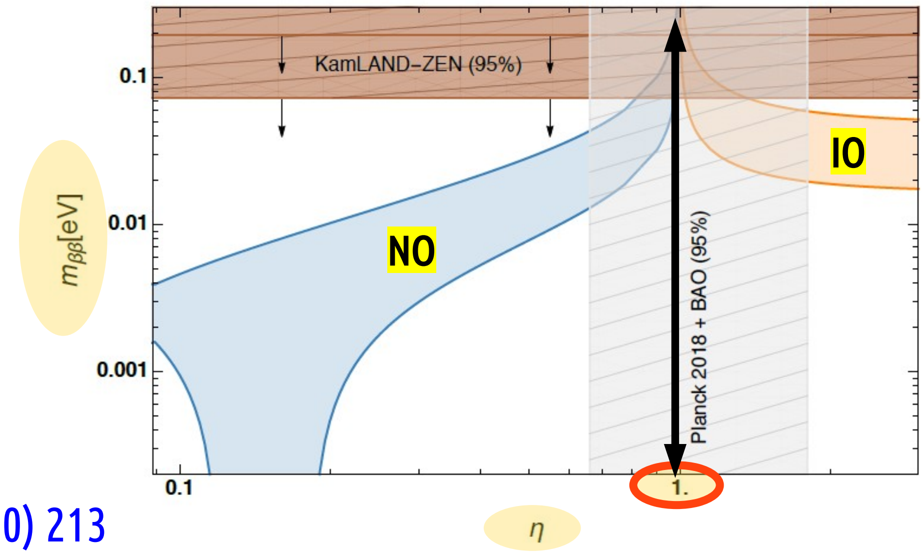
neutrinoless doublebeta decay

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

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

Nearly degenerate

Lattanzi et al JHEP 10 (2020) 213



degeneracy parameter

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
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Nearly degenerate

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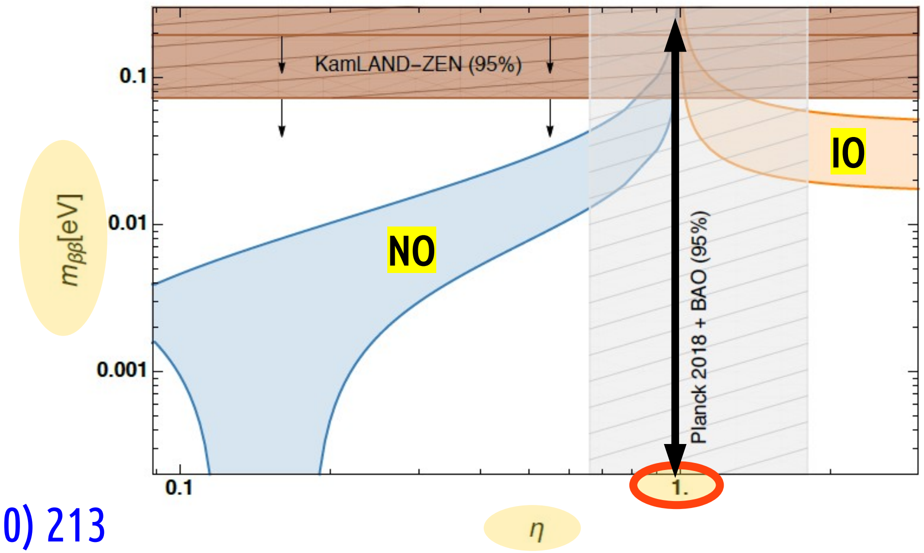
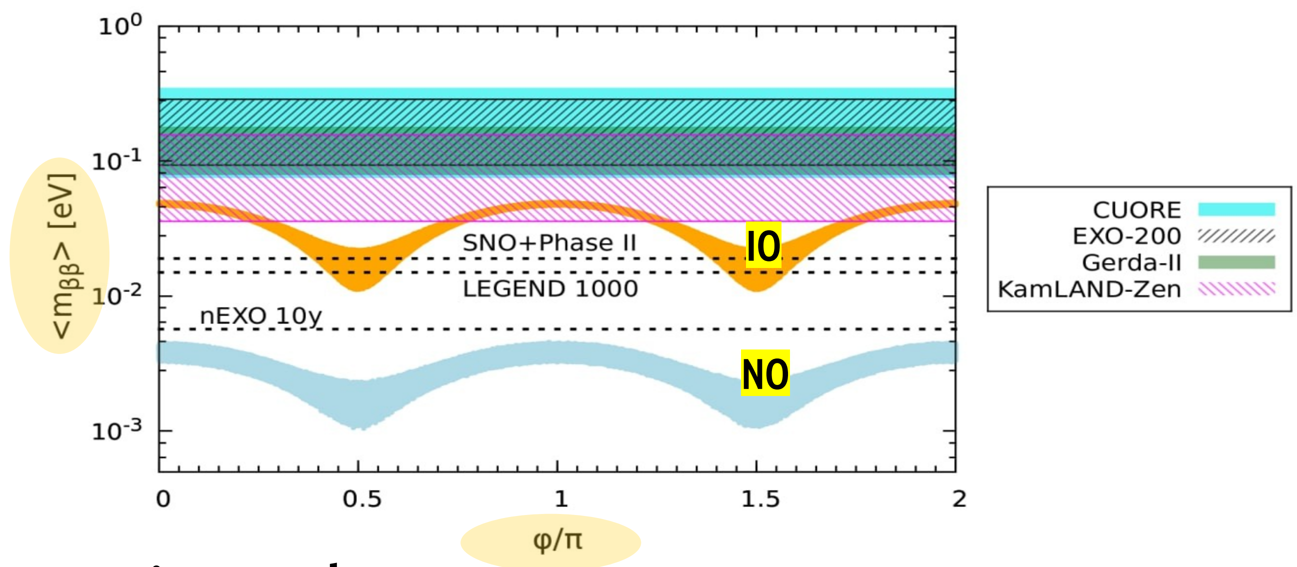


degeneracy parameter

- **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

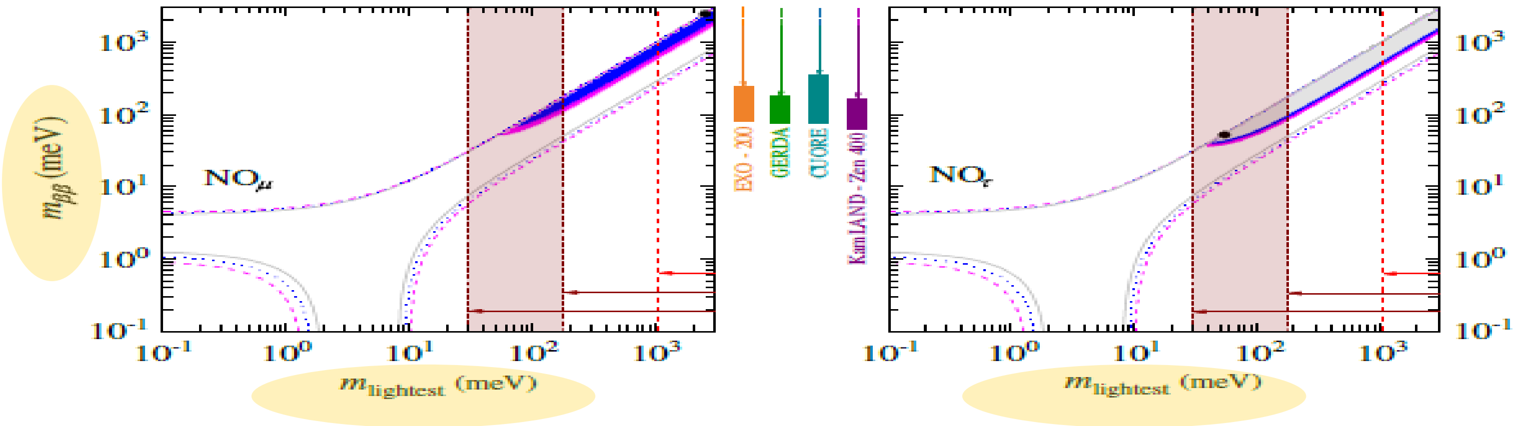
C Adams et al 2212.11099
Agostini et al. Science 365 (2019) 1445

- 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



3-massive case

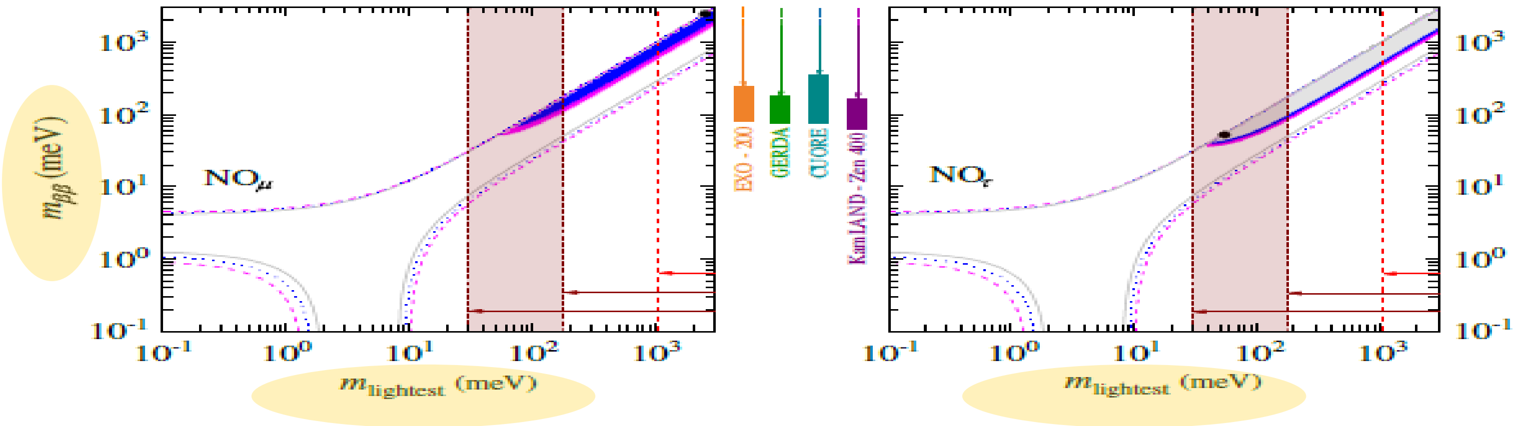
Lower bounds from family symmetries

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

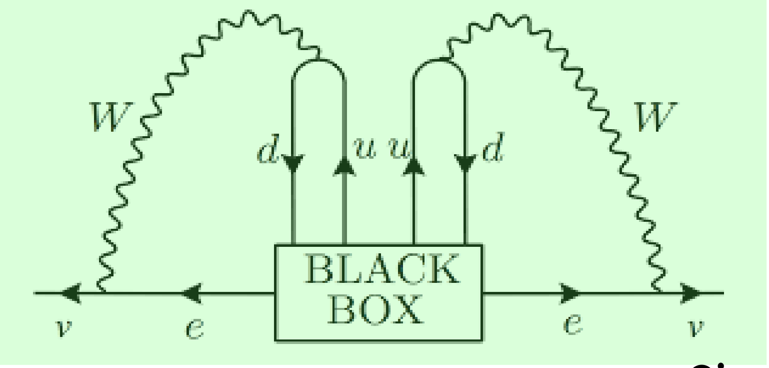


Significance

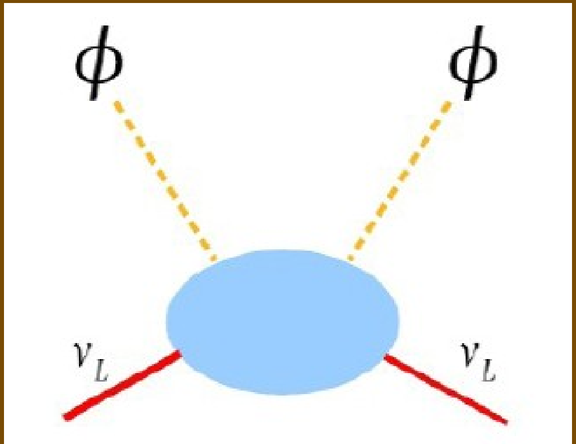
Schechter, Valle PhysRev D25 (1982) 2951

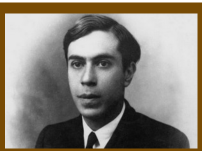
Duerr, Lindner, Merle JHEP06(2011)091

B.J.P. Jones 2108.09364 (TASI 2020)



Origin of neutrino mass



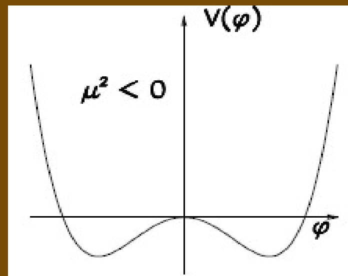


Origin of neutrino mass

SEESAW dynamics

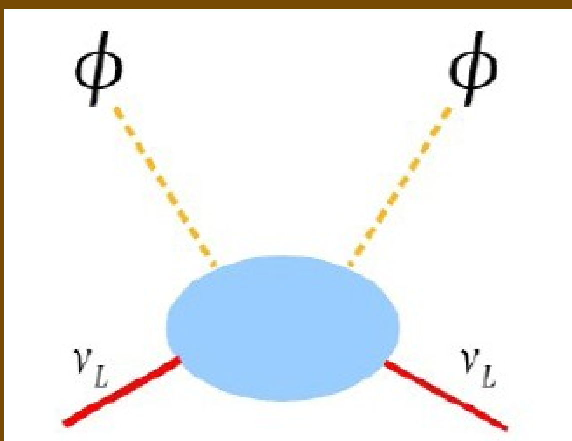
$$v_3 v_1 \sim {v_2}^2$$

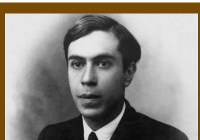
stability



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

JHEP03(2021)212 & JHEP07(2021) 029





Origin of neutrino mass

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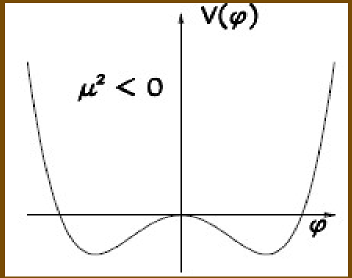
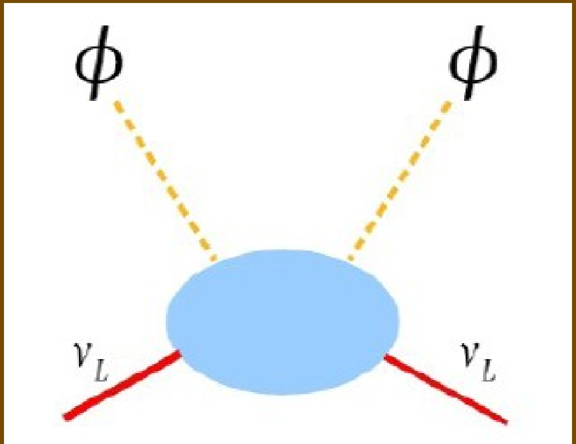


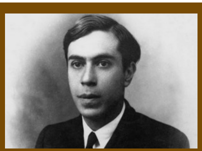
SEESAW dynamics

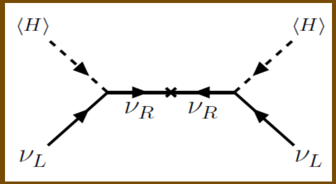
$$v_3 v_1 \sim {v_2}^2$$

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

JHEP03(2021)212 & JHEP07(2021) 029







TYPE I

Minkowski 77

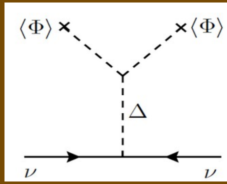
Gellman Ramond Slansky 80

Glashow, Yanagida 79

Mohapatra Senjanovic 80

Lazarides Shafi Weterrich 81

Schechter-Valle 80 & 82



TYPE II

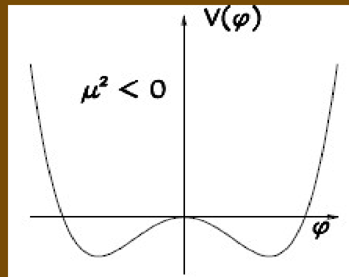
Schechter-Valle 80 & 82

L-R seesaw # of Rs = # Ls

SM seesaw # of singlets arbitrary

Origin of neutrino mass

stability

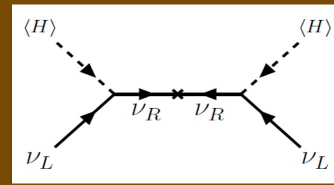


SEESAW
dynamics

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

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

JHEP03(2021)212 & JHEP07(2021) 029



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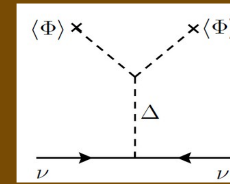

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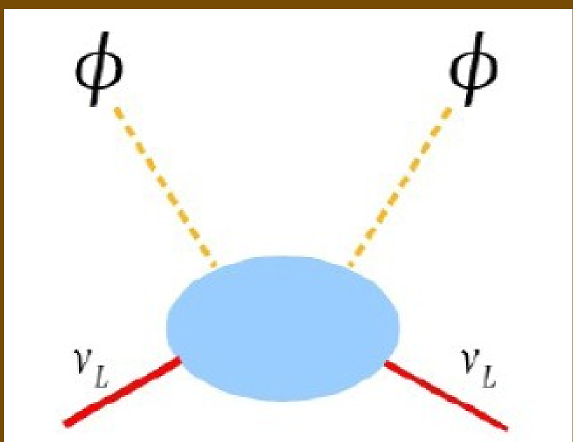
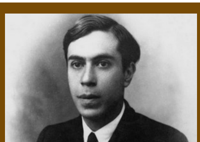


- MISSING PARTNER

(3,2) min viable type1 seesaw

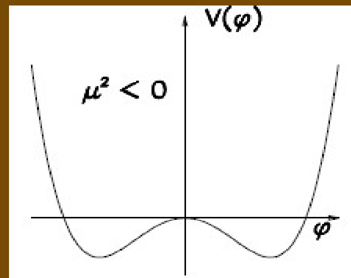
(3,1) scoto-seesaw template

$m_{\beta\beta}$



Origin of neutrino mass

stability

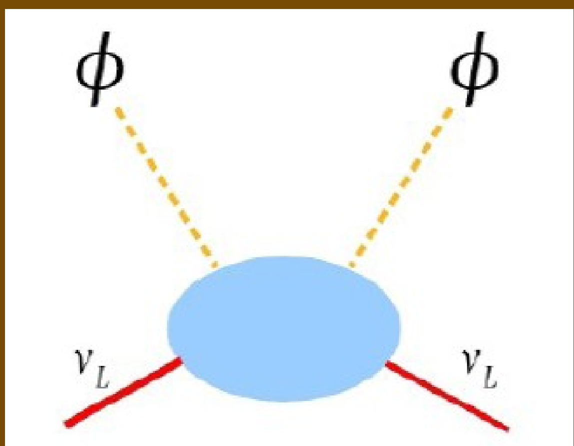


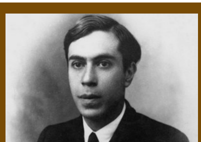
SEESAW dynamics

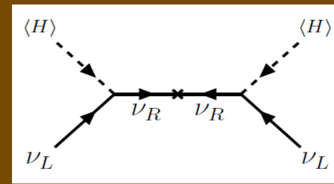
$$v_3 v_1 \sim v_2{}^2$$

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

JHEP03(2021)212 & JHEP07(2021) 029







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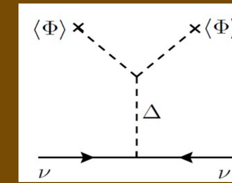


TYPE II

Schechter-Valle 80 & 82

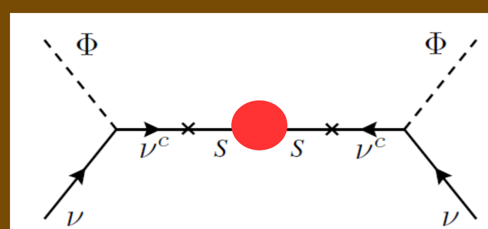
L-R seesaw # of Rs = # Ls

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

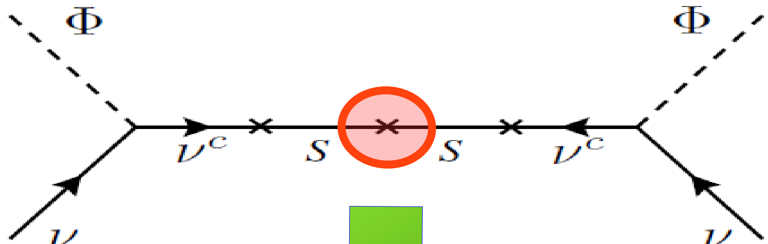
Akhmedov et al Phys.Rev.D53 (1996) 2752

PhysLettB368 (1996) 270

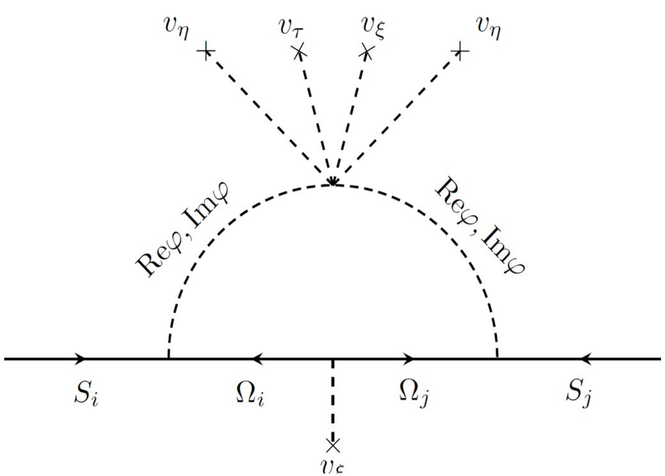
Malinsky et al PhysRevLett95(2005)161801

@jwvalle7

doubly protected inverse seesaw

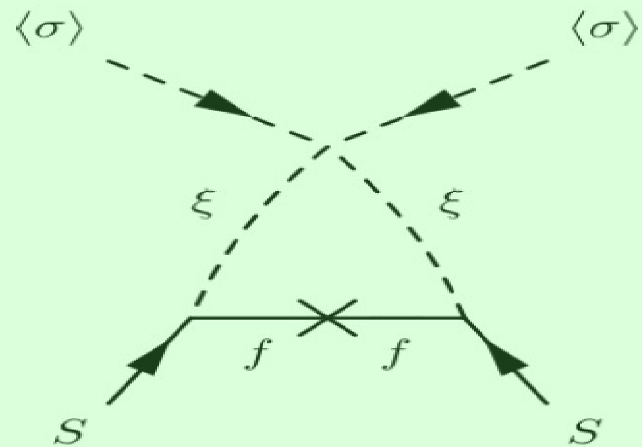


radiative
inverse seesaw



L-R scheme

:Cárcamo Hernández et al   JHEP 1902 (2019) 065



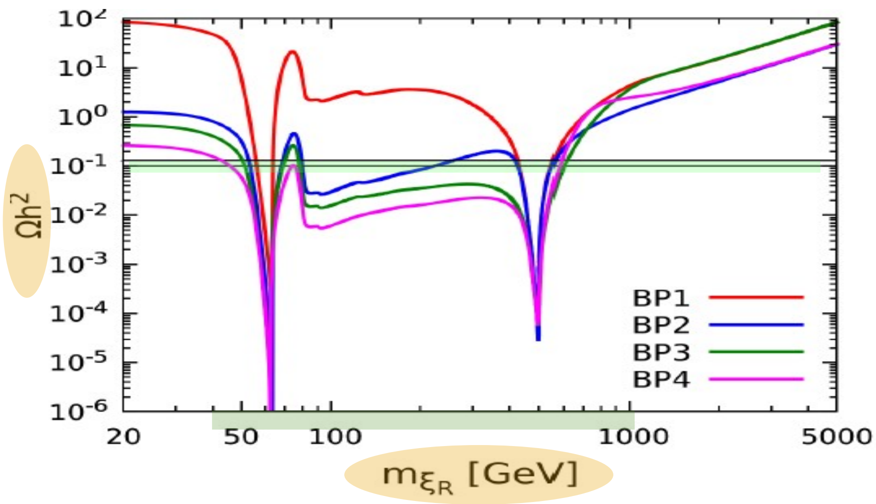
dark inverse seesaw

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

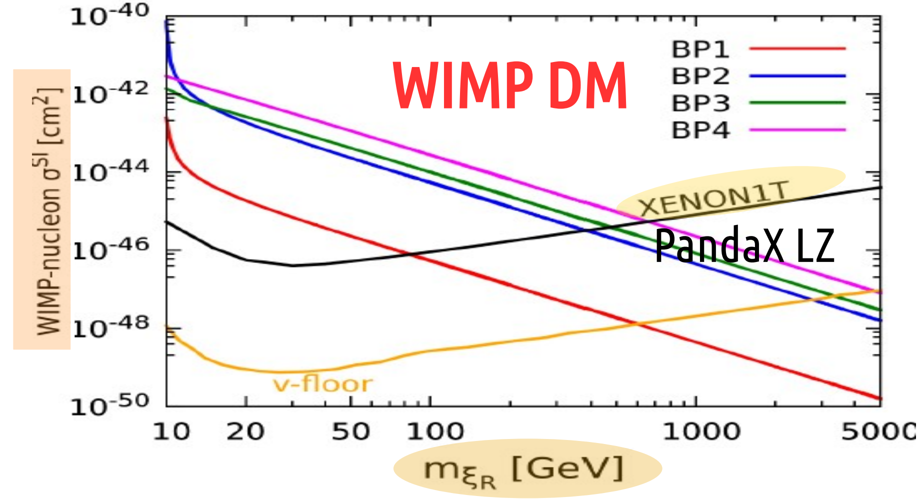
dark inverse typeI seesaw mechanism

LambdaCDM

Phys.Lett.B821 (2021) 136609

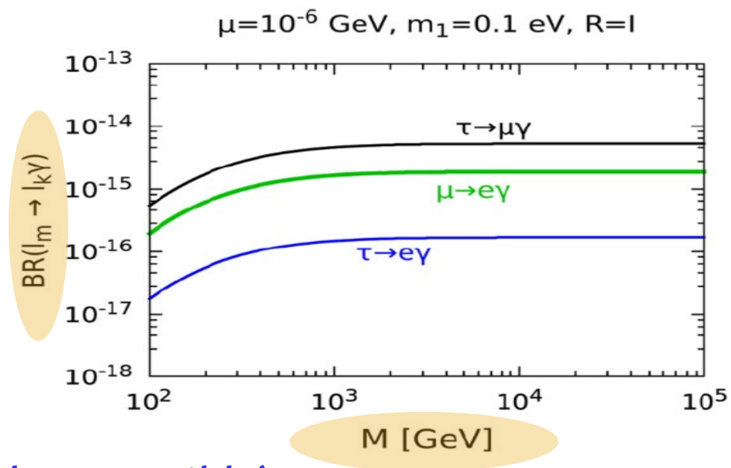


Xenon1T PhysRevLett.121.111302
PandaX Lux-Zepellin

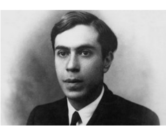


large cLFV from inverse type I seesaw

Mandal et al
Phys.Lett.B 821 (2021) 136609



(larger values possible)



@jwvalle9

linear seesaw & CDFII W mass anomaly

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

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

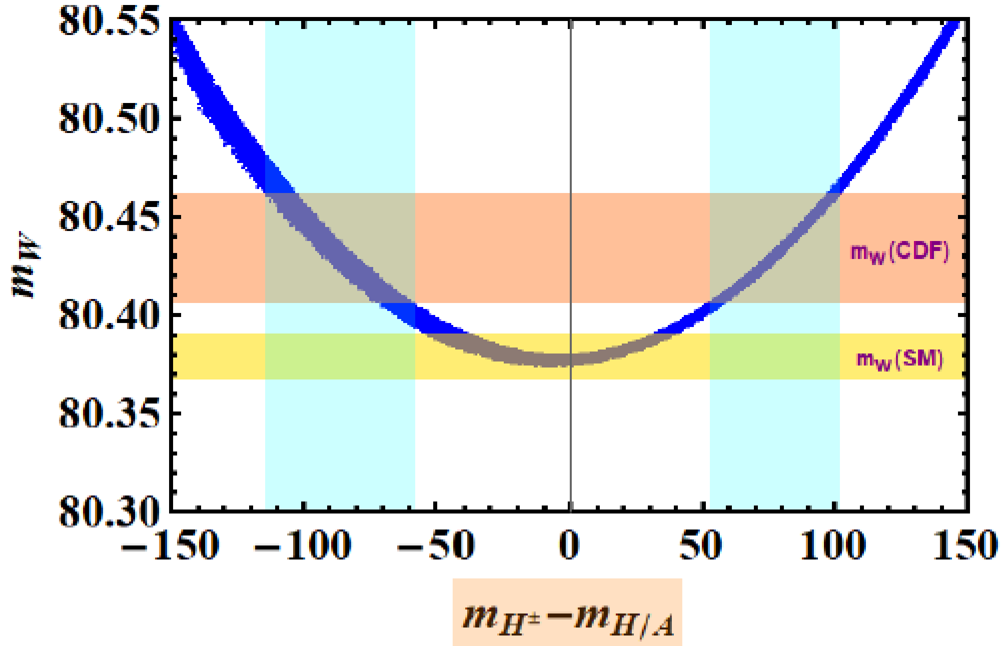
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M_R \\ M_L^T & M_R^T & 0 \end{pmatrix}$$

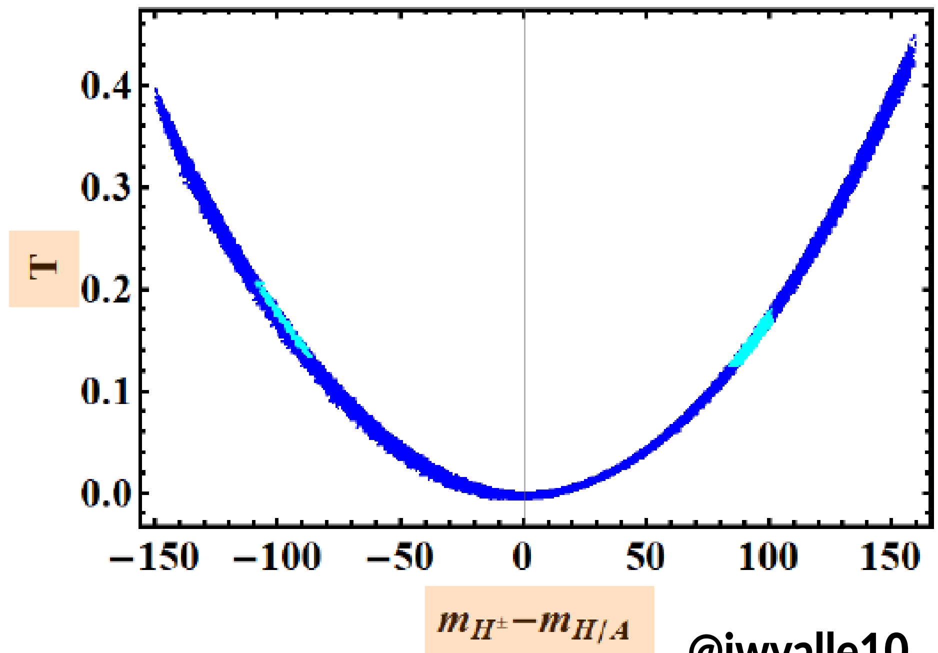
$$m_W^2 = m_W^2|_{\rm SM}\left(1 + \frac{s_W^2}{c_W^2 - s_W^2}\Delta r|_{\rm NP}\right)$$

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

Batra et al Phys.Lett.B 834 (2022) 137408

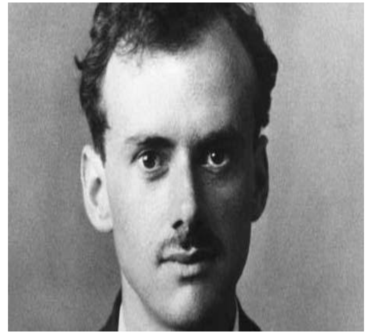
all 1sigma, except for CDF band, which is 3

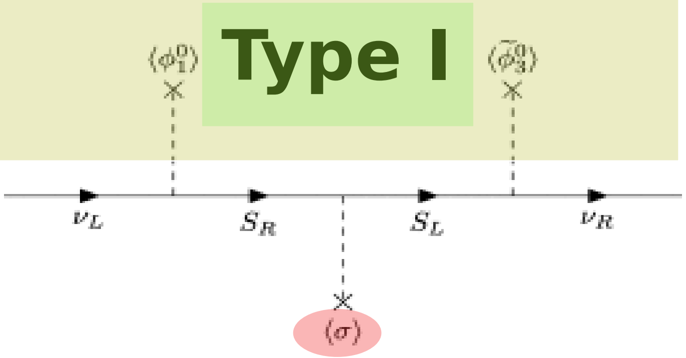


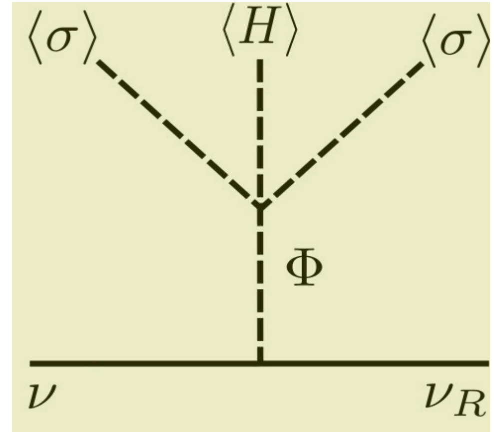


@jwvalle10

Seesawing a la



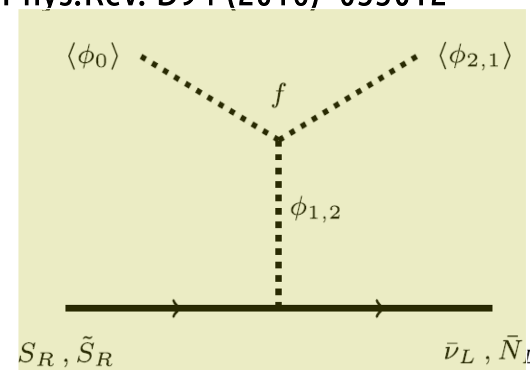




Type II

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



Phys.Lett.B 810 (2020) 135829

Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

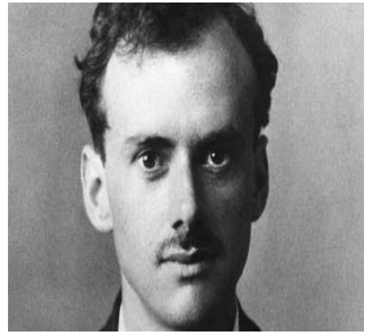
Phys.Rev. D98 (2018) 035009

Phys.Lett. B781 (2018) 122-128

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

Phys.Lett. B755 (2016) 363-366

seesawing a la



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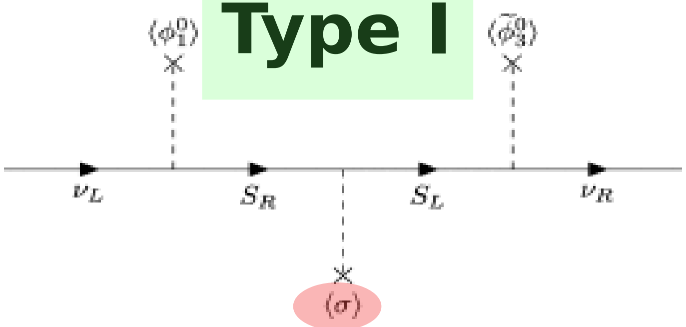

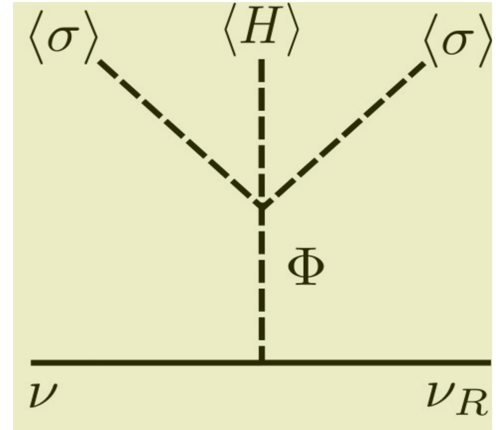

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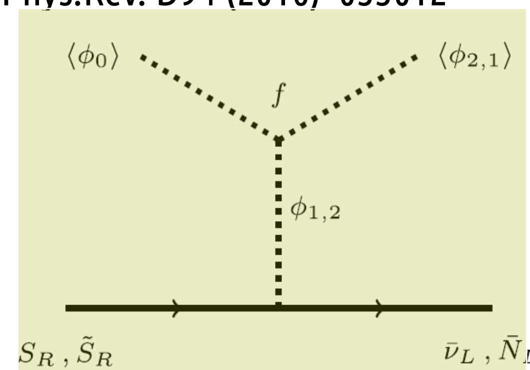

symmetry protecting small neutrino mass

+ Diracness

Peccei-Quinn symmetry

$$m_\nu^D \simeq \frac{y^{\nu_1}(y^S)^{-1}(y^{\nu_2})^T}{\sqrt{2}}\,\frac{v_1 w}{v_\sigma}.$$

SU3L (← w)

PQ (← v_σ)

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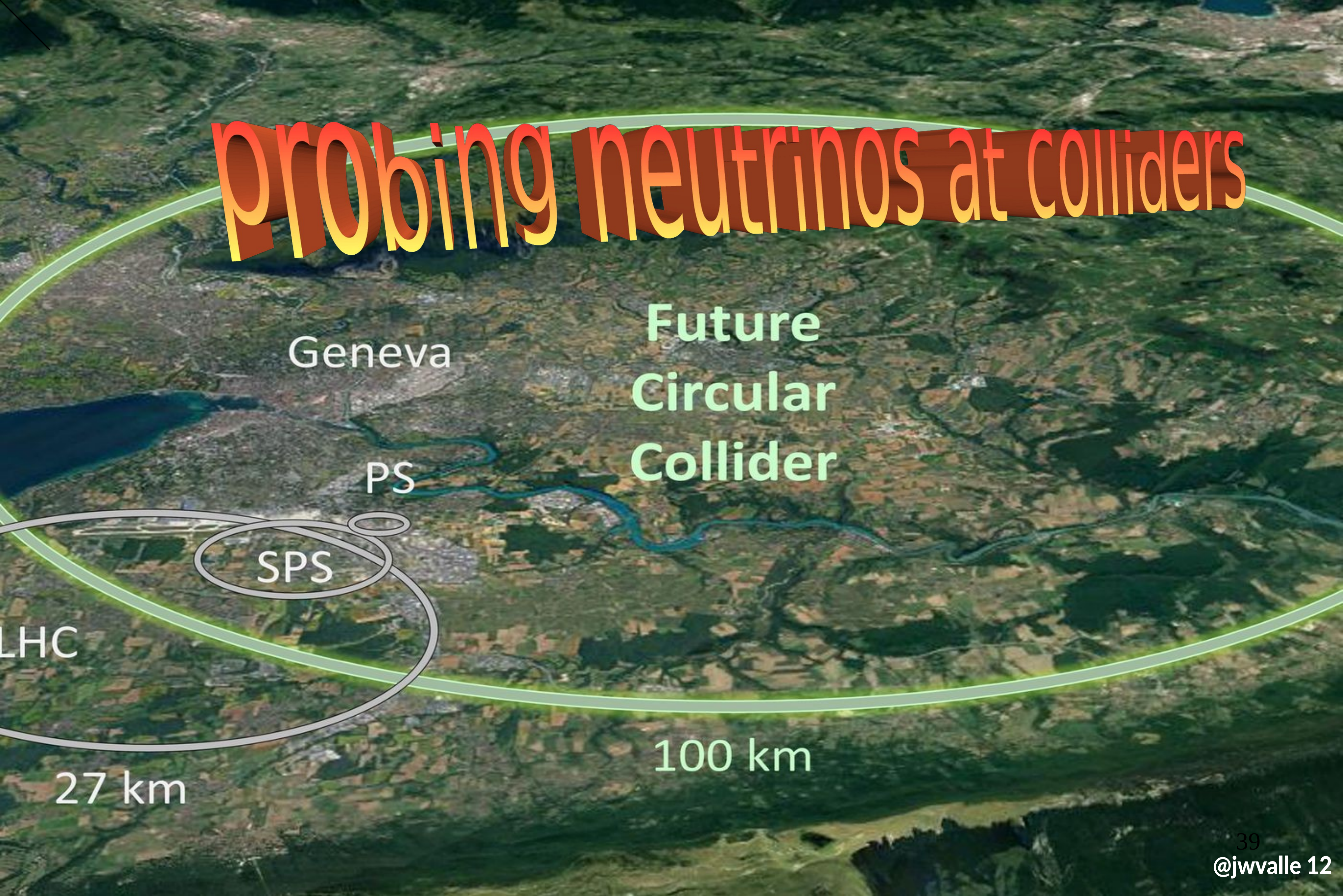
probing neutrinos at colliders

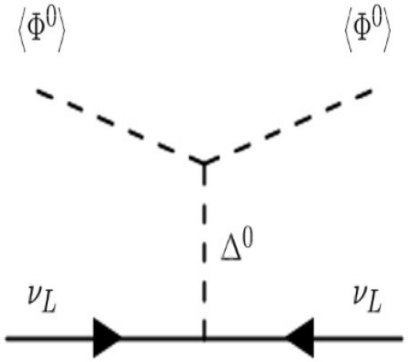


simplest seesaw

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

Schechter & JV PRD22 (1980) 2227

PRD25 (1982) 774



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

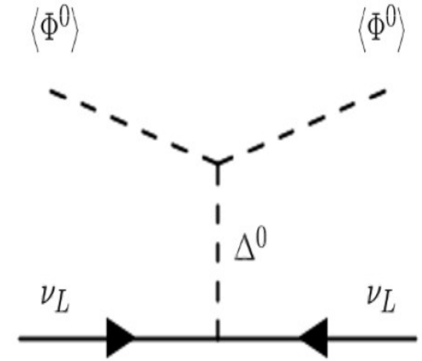
seesaw mediator produced in @ e+e- / pp collisions

Miranda et al PLB 829 (2022) 137110

simplest seesaw

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

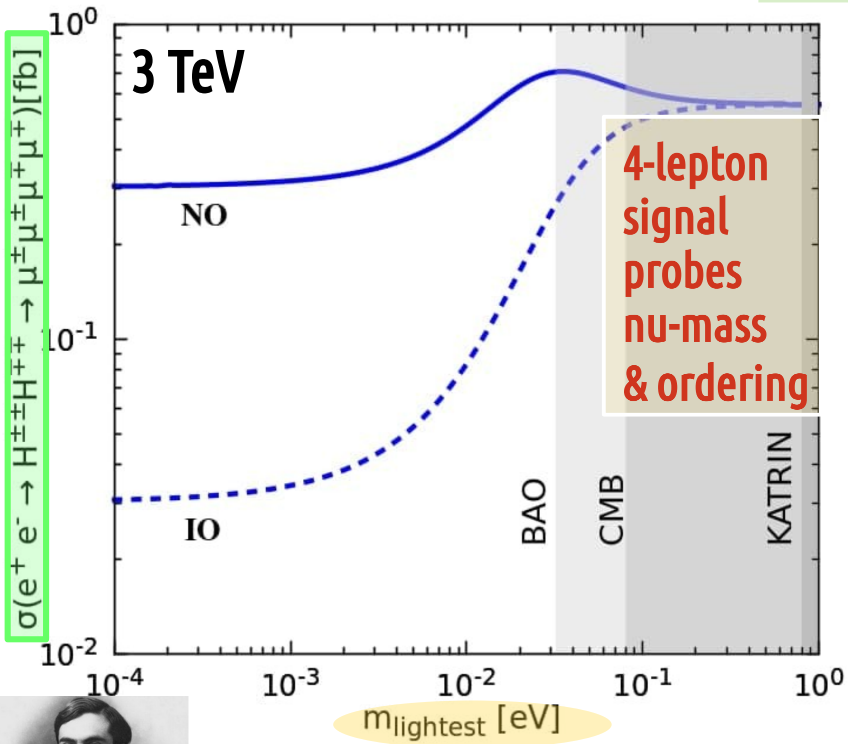
Schechter & JV PRD22 (1980) 2227
PRD25 (1982) 774

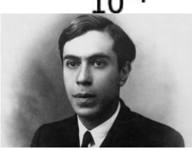


seesaw mediator produced in @ e+e- / pp collisions

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

Miranda et al PLB 829 (2022) 137110





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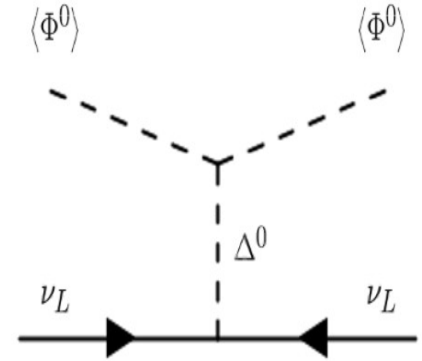
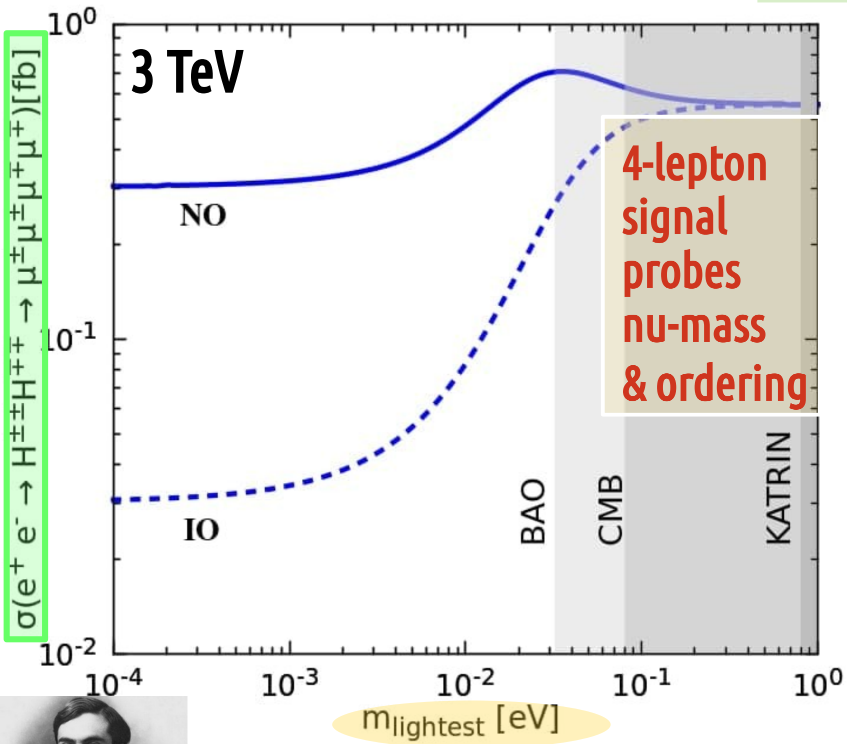
PRD25 (1982) 774

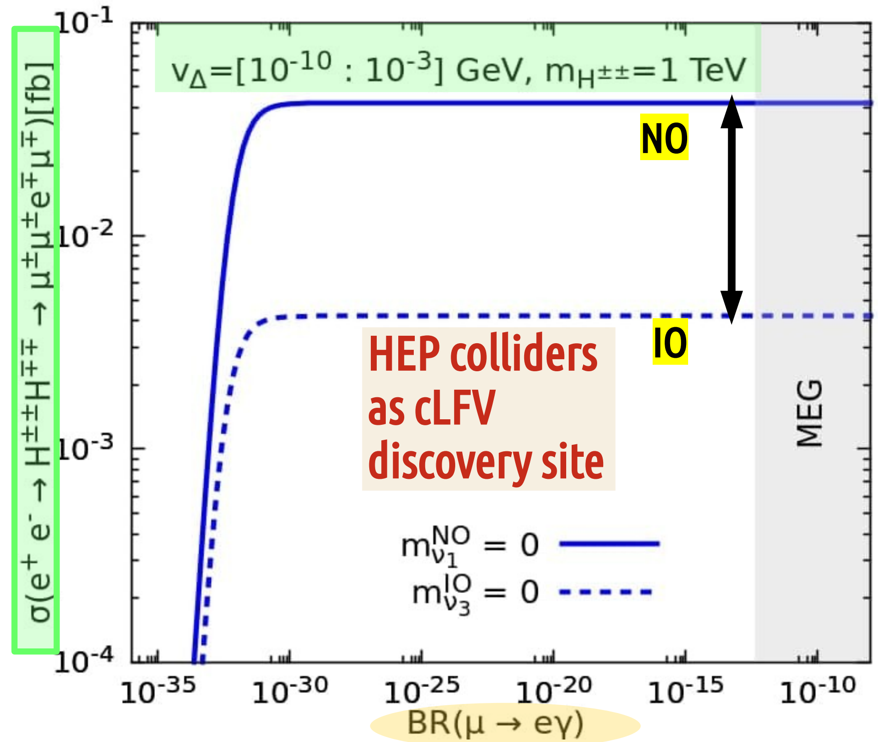


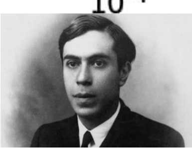
seesaw mediator produced in @ e+e- / pp collisions

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



Miranda et al PLB 829 (2022) 137110





PROBING NEUTRINO PROPERTIES AT COLLIDERS

Will not discuss NHL neutrino mass mediators in Type-I seesaw

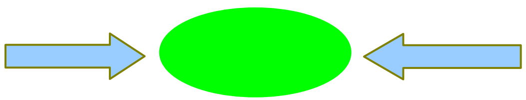
See, e.g. CMS Phys.Rev.Lett. 120 (2018) 22, 221801

PROBING NEUTRINO PROPERTIES AT COLLIDERS

Will not discuss NHL neutrino mass mediators in Type-I seesaw

See, e.g. CMS Phys.Rev.Lett. 120 (2018) 22, 221801

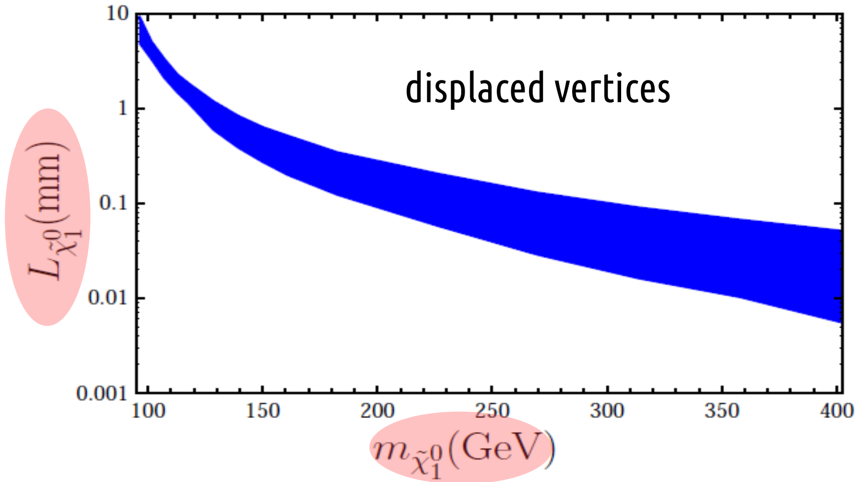
LSP from cascade squark & gluino decays



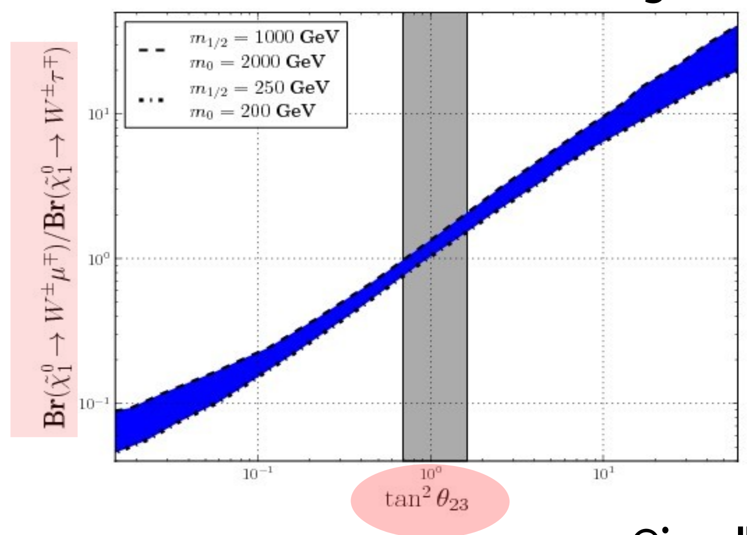
De Campos et al
Phys.Rev. D86 (2012) 075001

$$\tilde{\chi}_1^0 \rightarrow W^{\pm} l_i^{\mp}$$

Lightest neutralino decay length

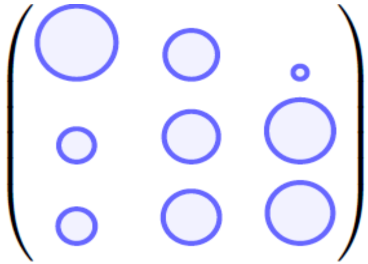


Lightest neutralino decay correlates with atm angle

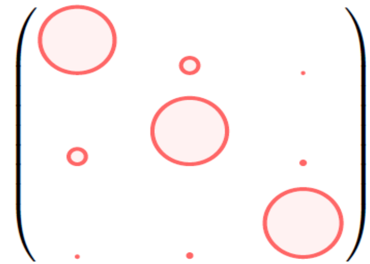


flavour legacy of oscillations

Q/L mixing pattern

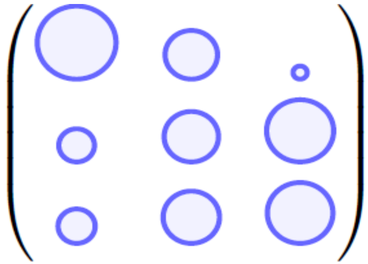


versus

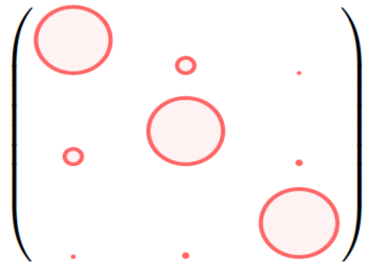


flavour legacy of oscillations

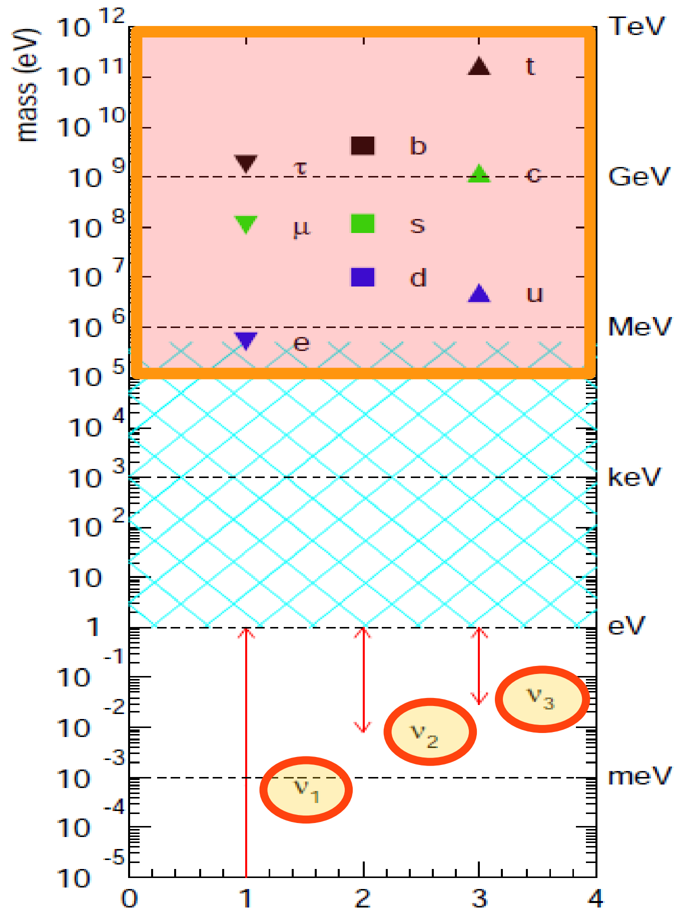
Q/L mixing pattern



versus

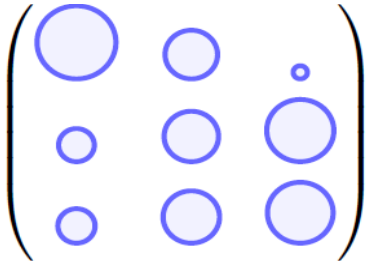


Q/L mass hierarchies

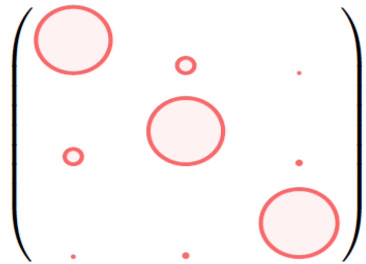


flavour legacy of oscillations

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

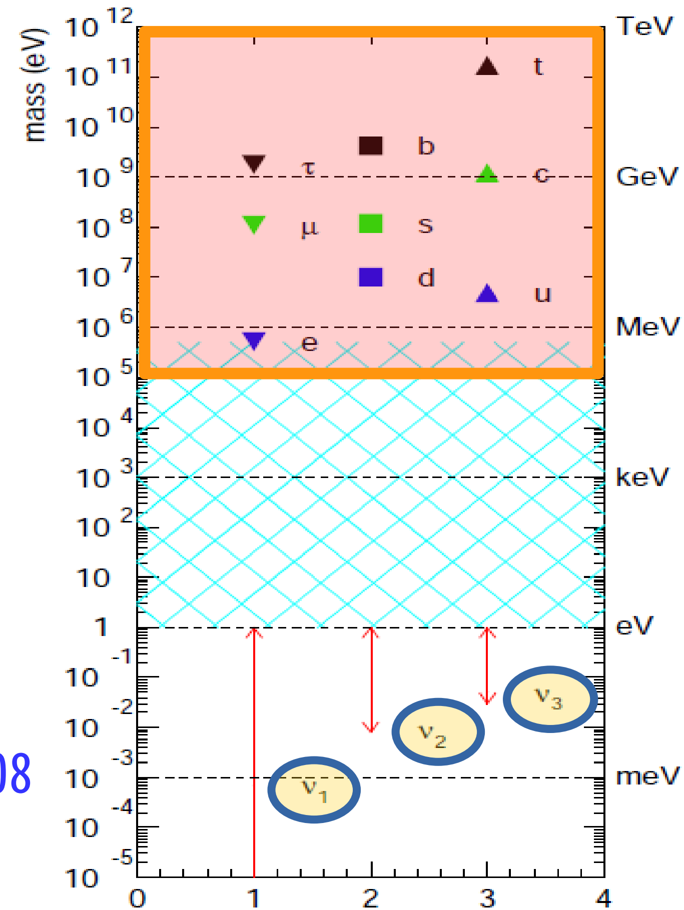
King et al Phys. Lett. B 724 (2013) 68

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

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

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

De Anda et al Phys. Rev. D105 (2022) 055030



a more radical departure??

@jwvalle 15

Higgs discovery is not the last brick !

Higgs discovery is not the last brick !

Oscillation discovery brought neutrinos to the spotlight

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

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

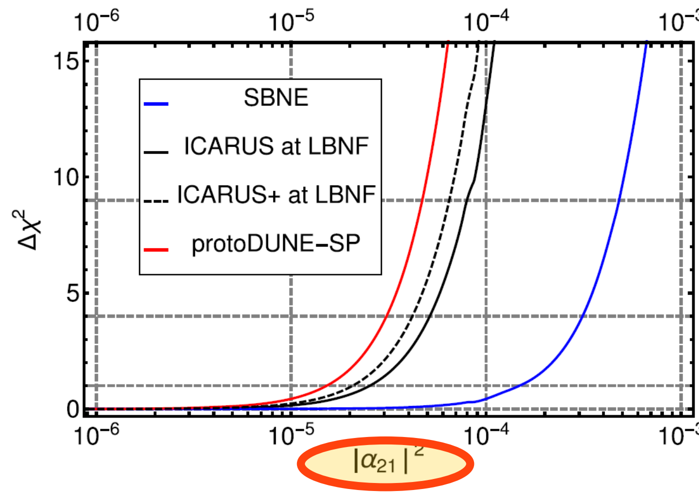
robustness

unitarity test

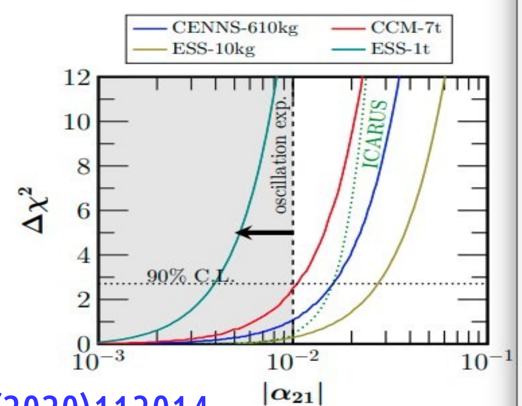
$$\begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

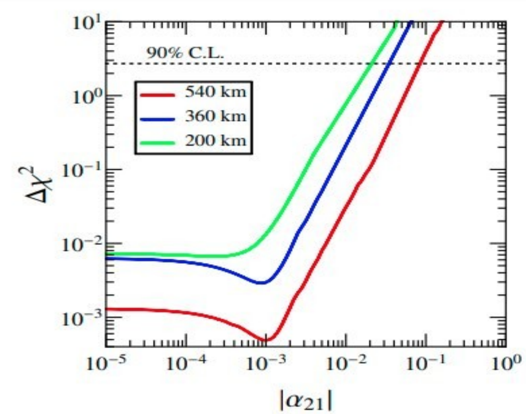
near measurements needed
Shao-Feng Ge et al
Phys.Rev. D95 (2017) 033005

	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





ESSnuB

PhysRevD102(2020)113014

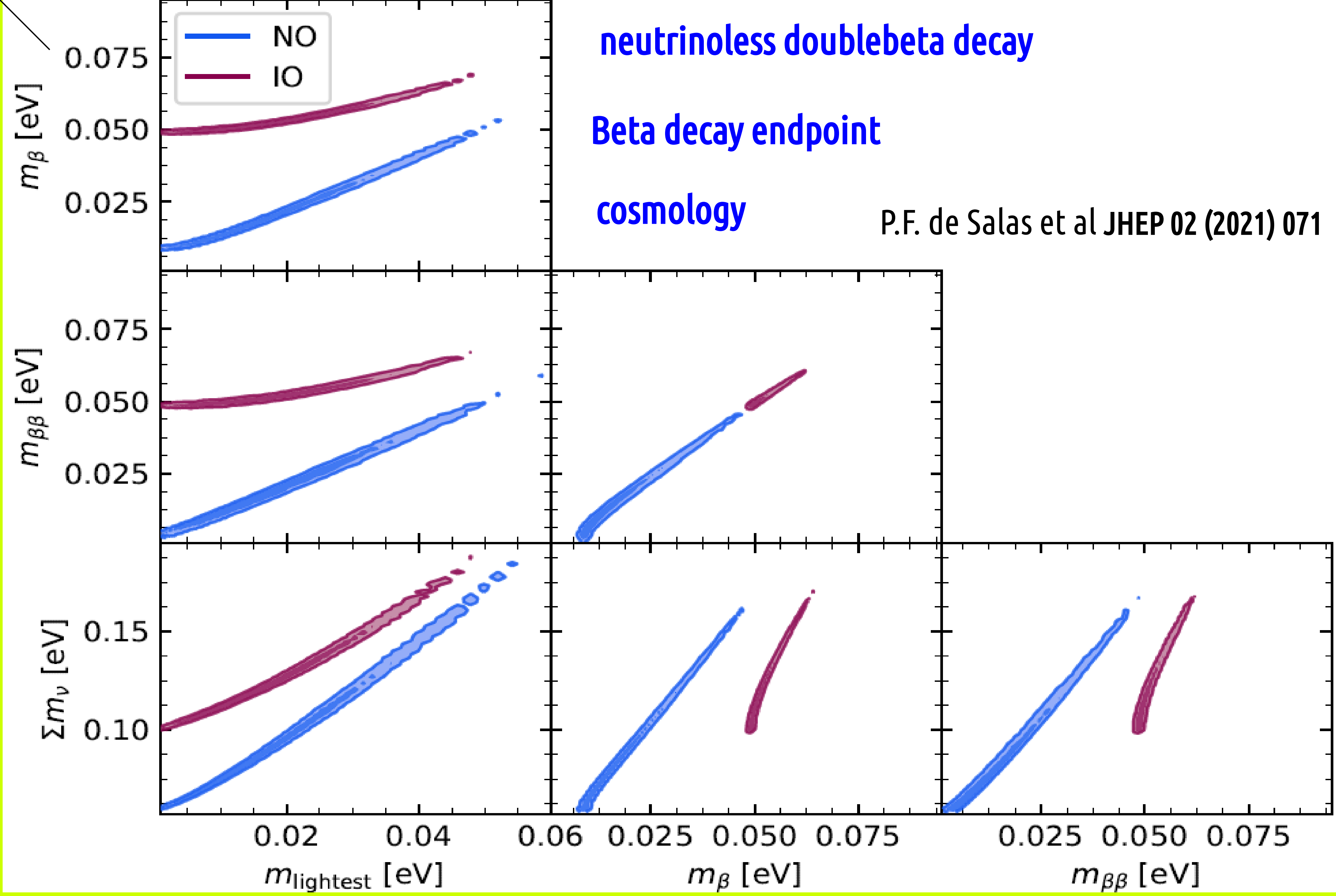
PRD106(2022)07501

neutrinoless doublebeta decay

Beta decay endpoint

cosmology

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



5D warped flavour dynamics

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'

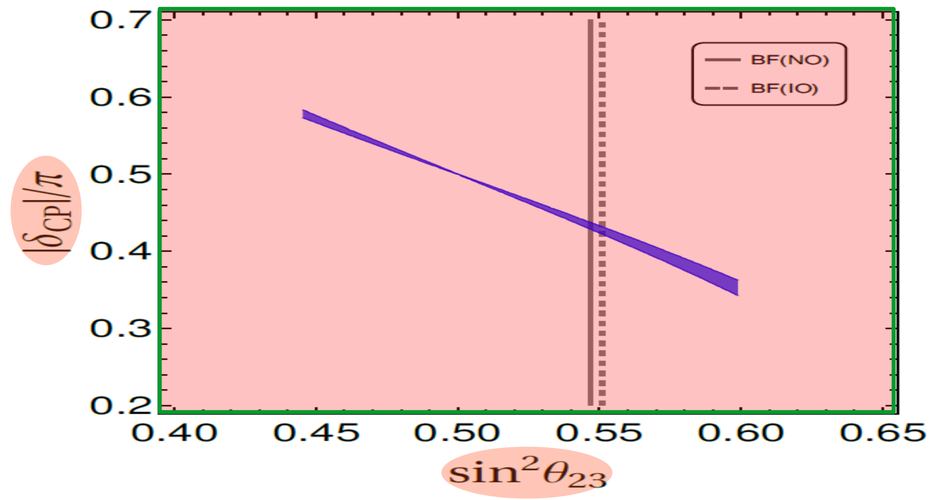
$$\cos^2\theta_{12}\cos^2\theta_{13} = \frac{2}{3}$$ TM1 pattern

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

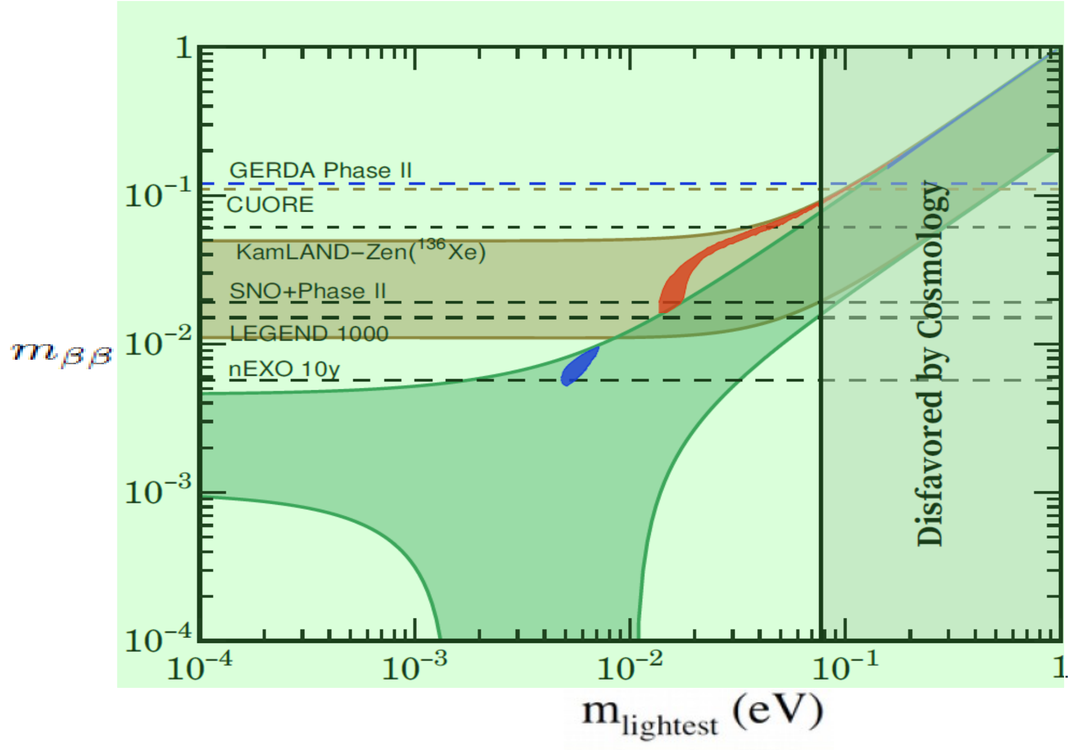
Chen et al Phys. Rev. D 102, 095014 (2020)

TM2 pattern

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



TM1



family symmetry from 6D orbifold

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

Phys.Lett.B 801 (2020) 135195

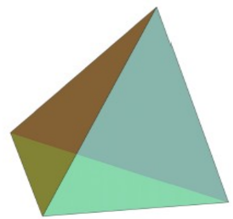
Phys.Rev.D 101 (2020) 11, 116012

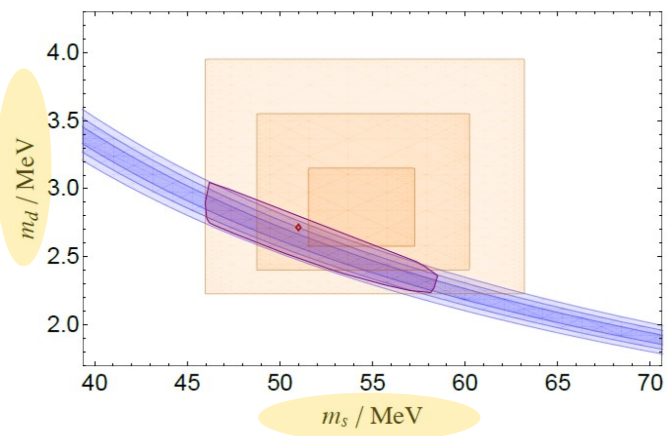
A4 family symmetry “derived”

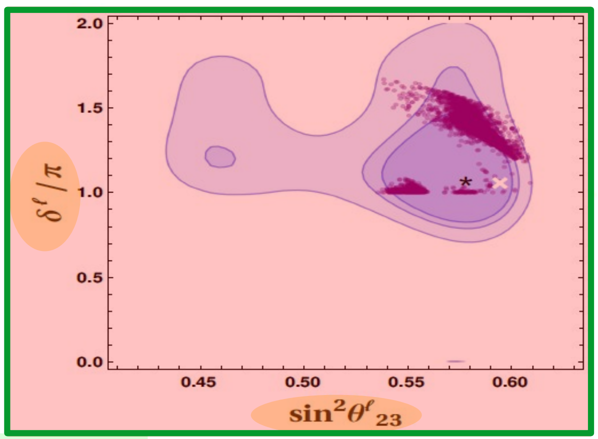
Phys.Rev.D 105 (2022) 055030

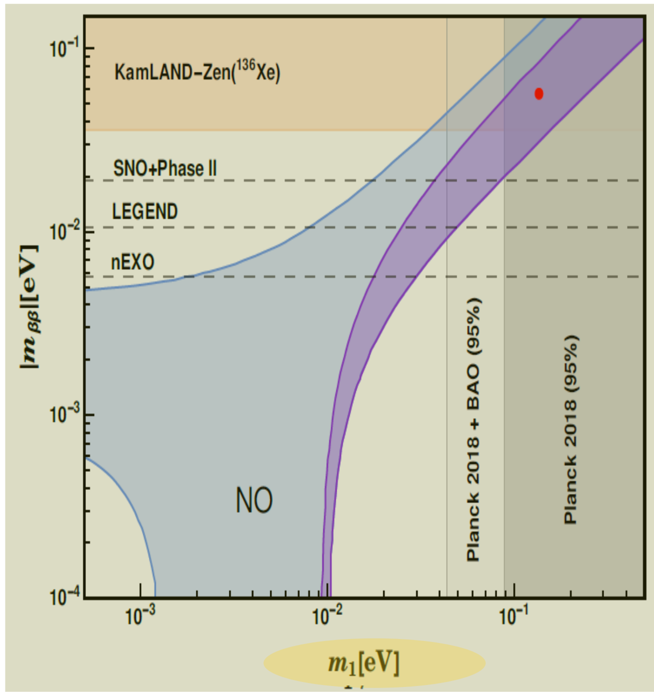
Golden Q-L relation

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

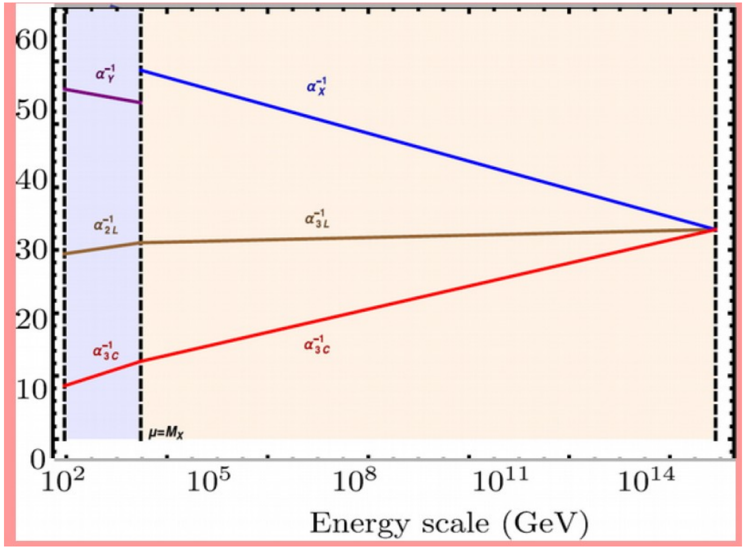








Good global fit of flavor observables



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

neutrino path to unification

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

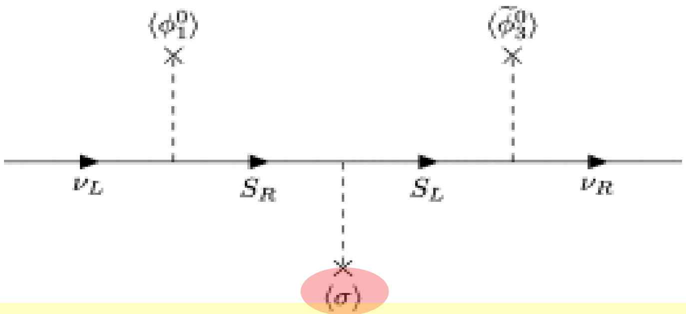
Deppisch et al Phys.Lett. B762 (2016) 432

why 3 families

Old 331 model

PRD22(1980)738

Diracness from PQ



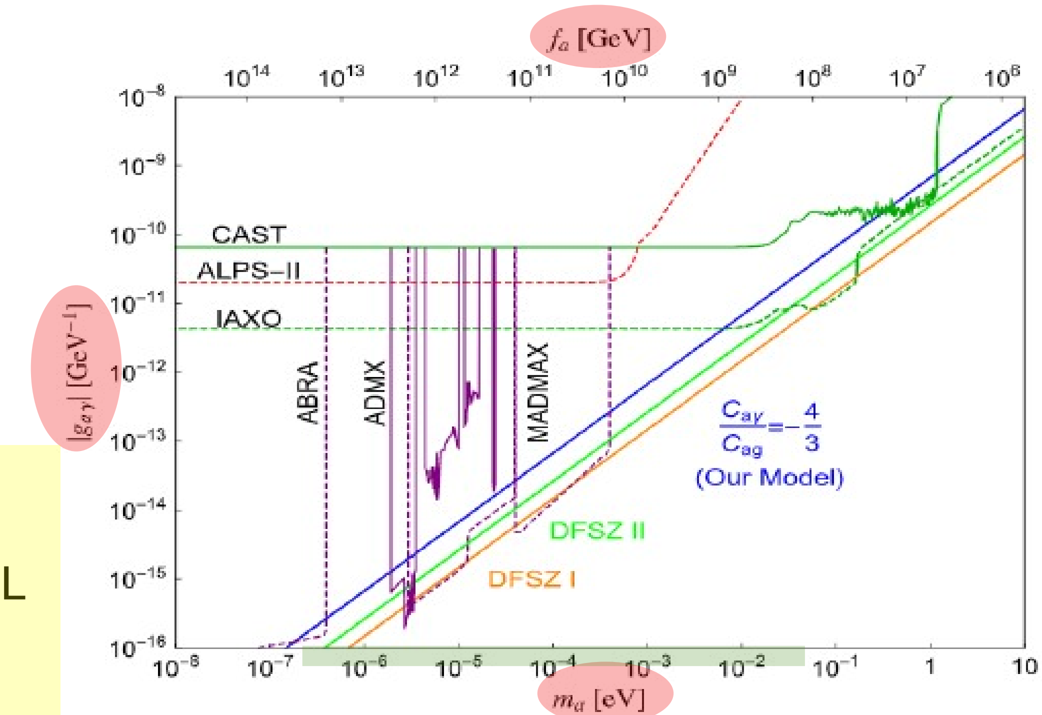
$$m_\nu^D \simeq \frac{y^{\nu_1}(y^S)^{-1}(y^{\nu_2})^T}{\sqrt{2}} \frac{v_1 w}{v_\sigma}.$$

SU3L

PQ

Phys.Lett.B 810 (2020) 135829

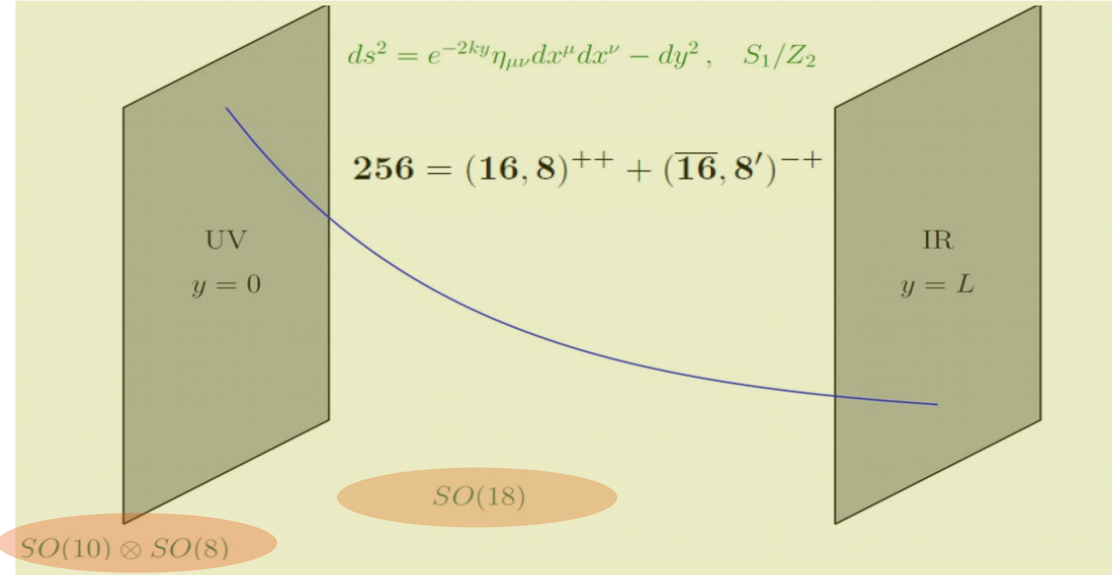
From *Physics Letters B 810 (2020) 135829*



tree-level quark FCNC

new path to family unification

inspired by beauty of neutrinos in SO10



promote M4 to AdS5

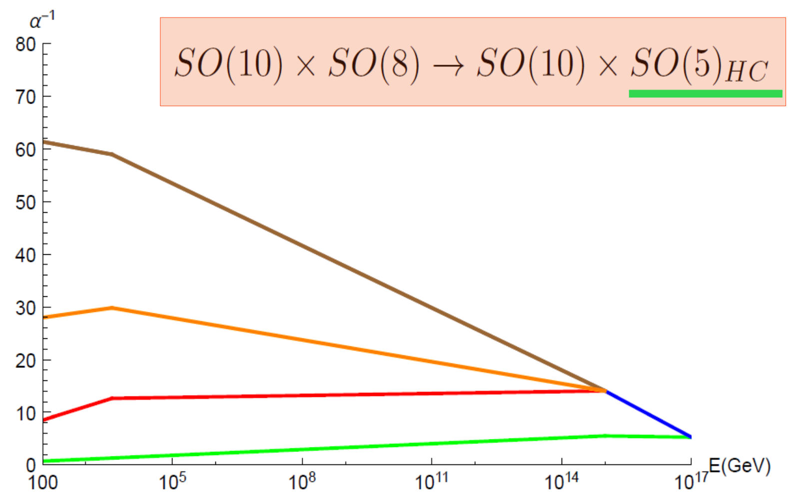
Reig, Valle, Vaquera-Araujo, Wilczek
PLB774 (2017) 667-670

use orbifold BC to decouple mirrors

unwanted chiral families bound
by new hypercolor force above TeV

new spectroscopy

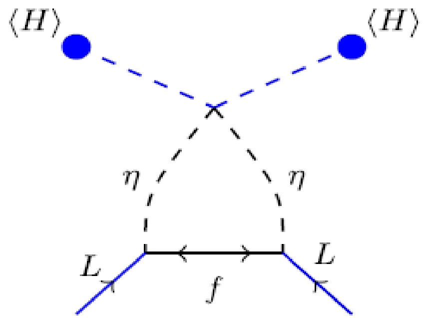
Reig, JV, Wilczek
Phys.Rev. D98 (2018) 095008



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

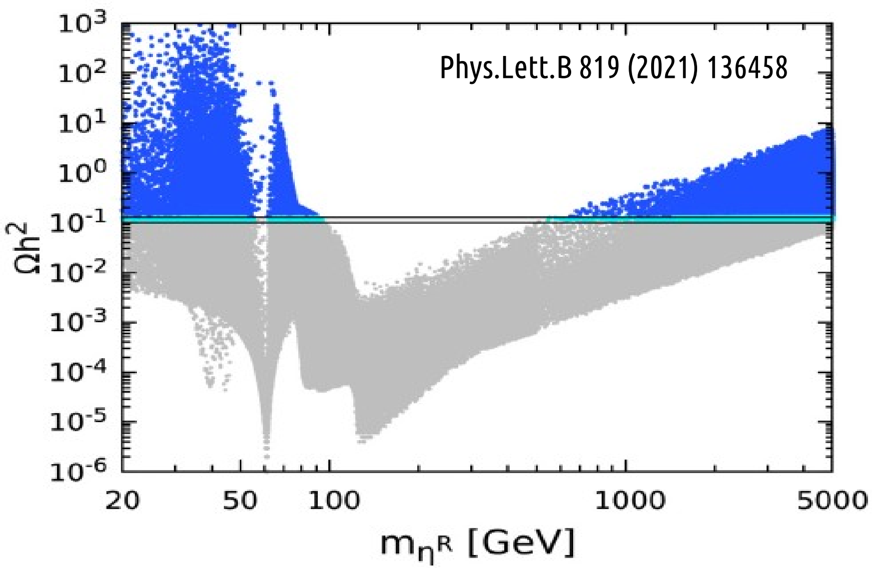
scotoseesaw : combining WIMP & seesaw paradigms

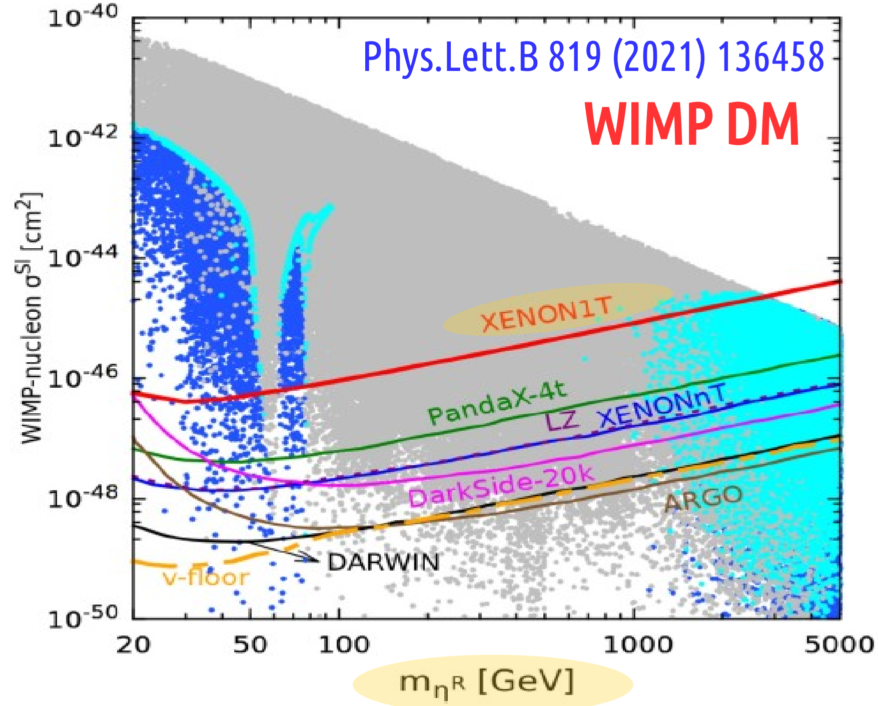
Loop solar scale

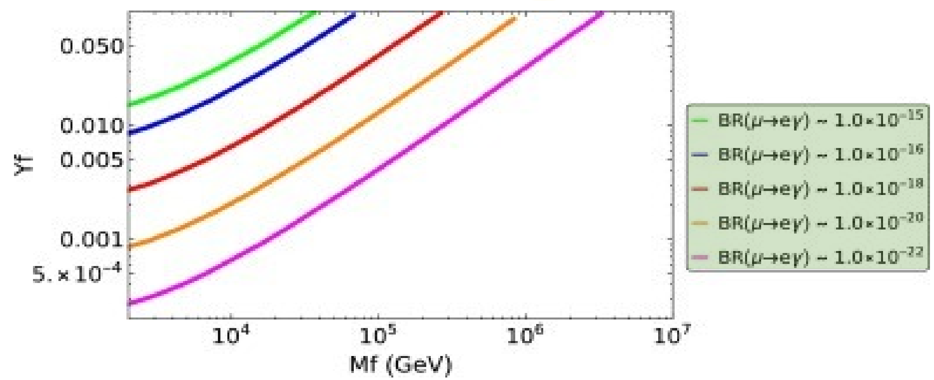


$$\Delta m^2_{\rm ATM} = \left(\frac{v^2}{2M_N}\mathbb{Y}_N^2\right)^2 , \quad \Delta m^2_{\rm SOL} \approx \left(\frac{1}{32\pi^2}\right)^2 \left(\frac{\lambda_5 v^2}{M_f^2 - m_\eta^2} M_f \mathbb{Y}_f^2\right)^2$$

Tree atm scale from type-I seesaw



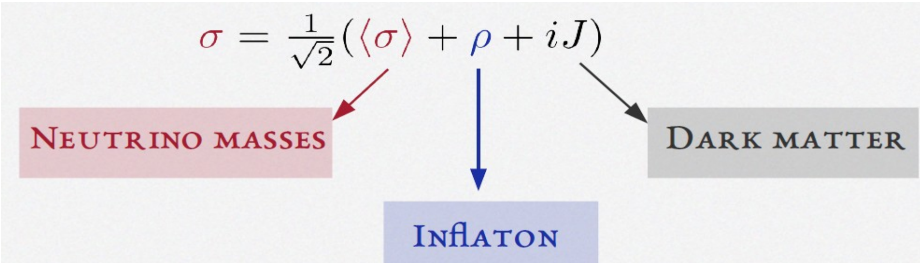




$0\nu\beta\beta$ lower bound

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

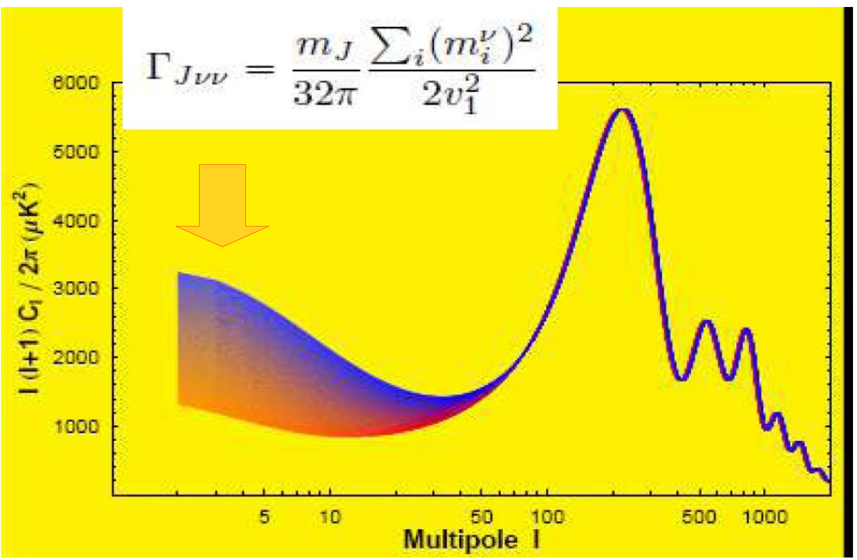
X-rays from DM decay

$\mathbf{J} \to \gamma\gamma$

Lattanzi et al PRD88 (2013) 063528

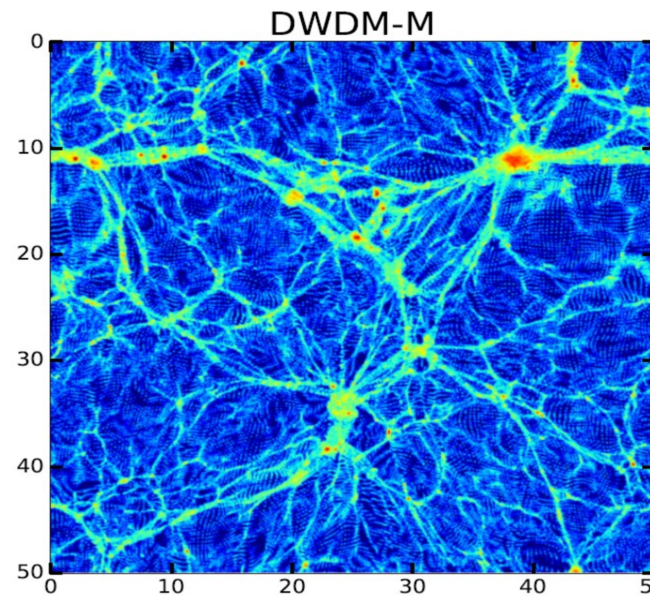
Consistency with CMB

Lattanzi & Valle, PRL99 (2007) 121301



large
scale
structure

Kuo et al
JCAP 1812 (2018) 026



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