

# the legacy of neutrino oscillations

JOSÉ W F VALLE

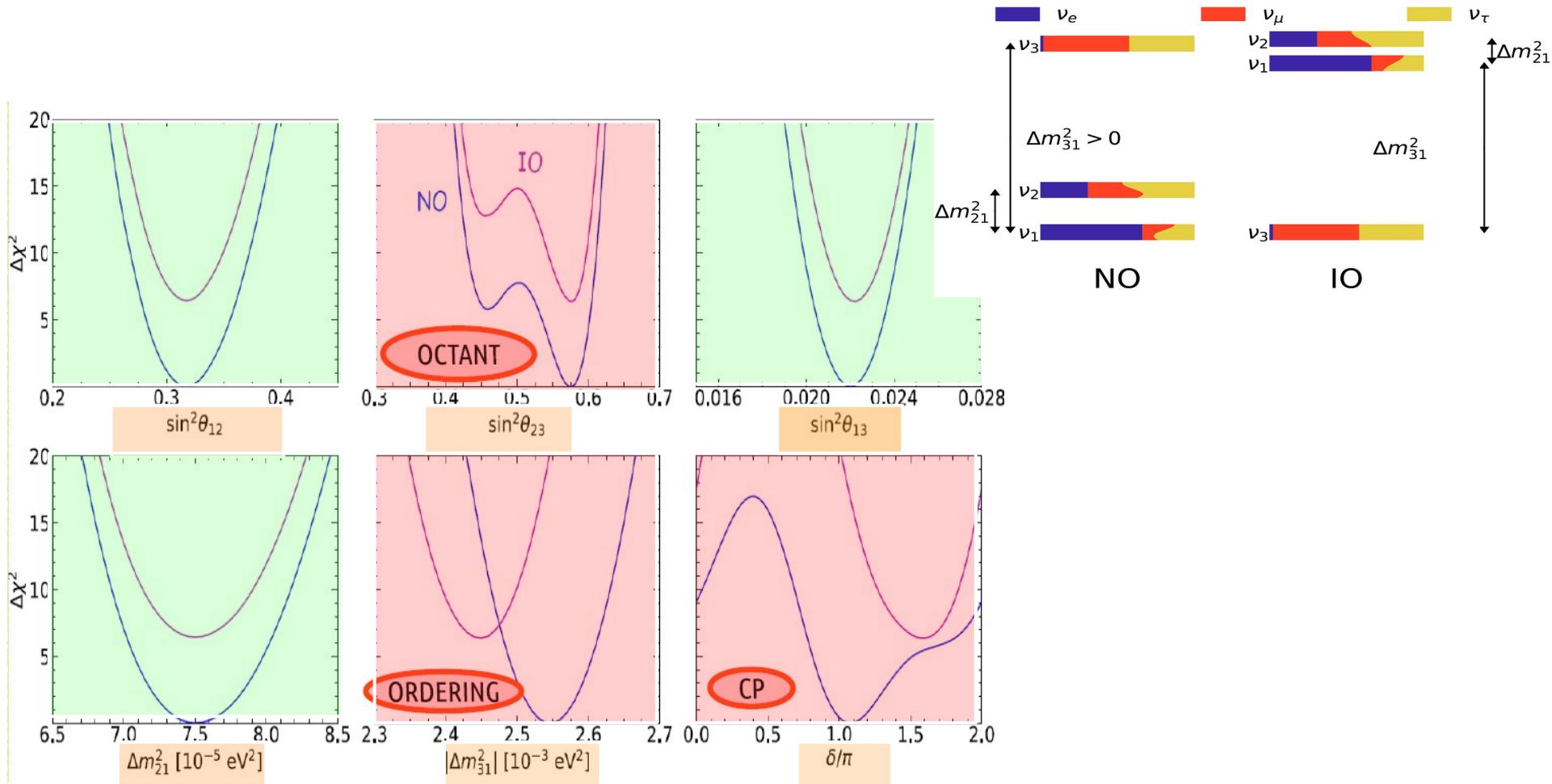


**ASTROPARTICLES**  
Astroparticles and High Energy Physics Group

# 3-neutrino oscillation status

PF de Salas et al JHEP02(2021)071

<https://zenodo.org/record/4593330#.YFoBVWNKjlo>



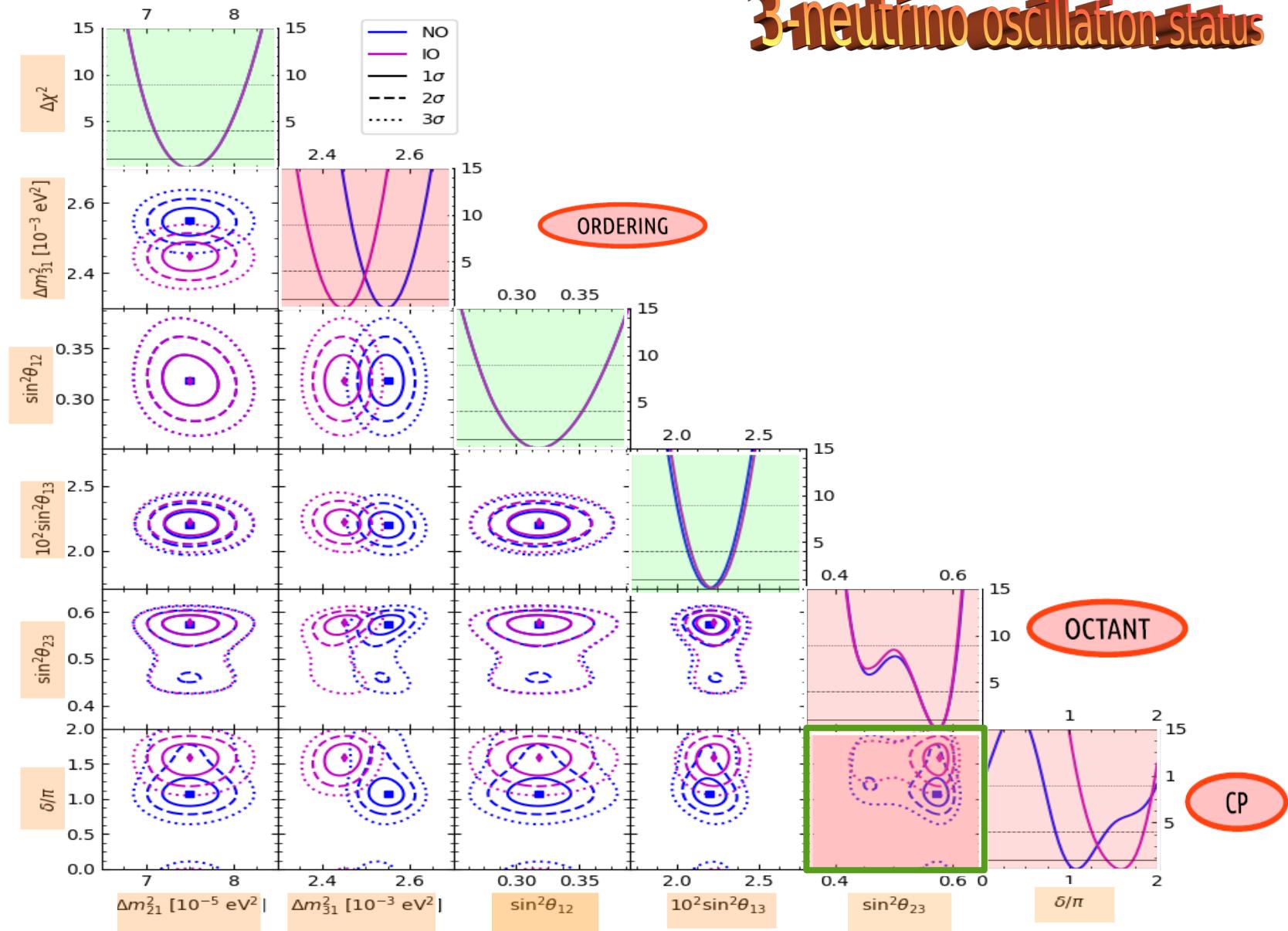
Similar results from Bari and NuFit groups

@jwvalle2

# 3-neutrino oscillation status

PF de Salas et al JHEP02(2021)071

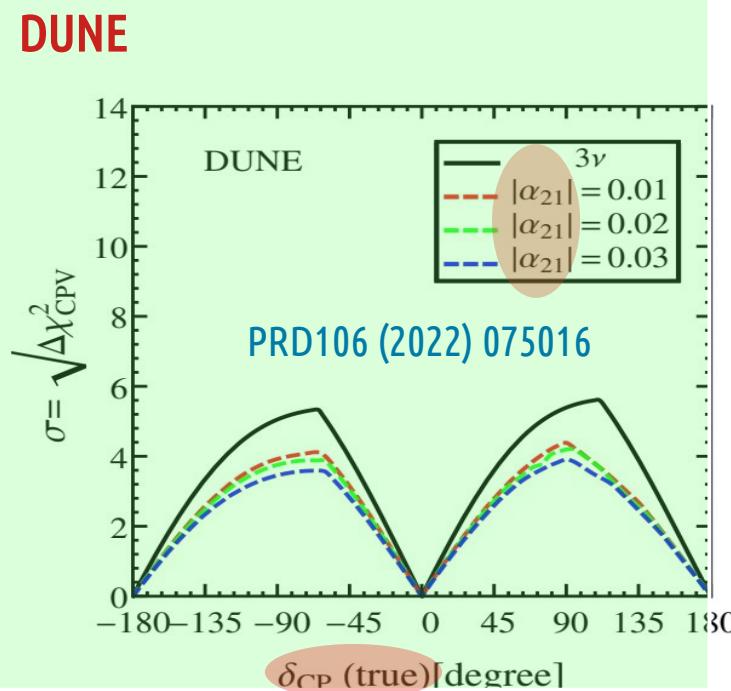
<https://zenodo.org/record/4593330#.YFoBVWWNKjio>



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

@jwvalle3

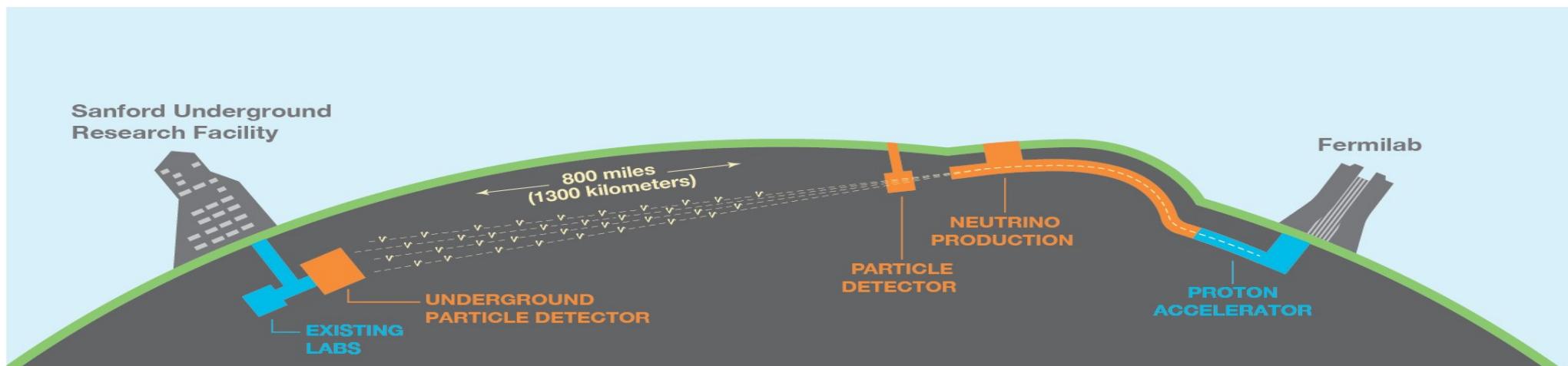
PhysRevLett117(2016)061804  
 New J.Phys. 19 (2017) 9, 093005  
 PhysRevD97 (2018) 095026



DUNE 2008.12769

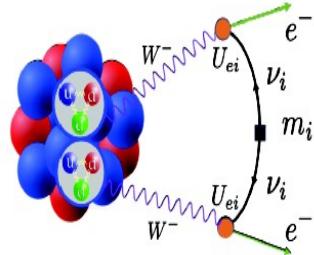
Hyper-K

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

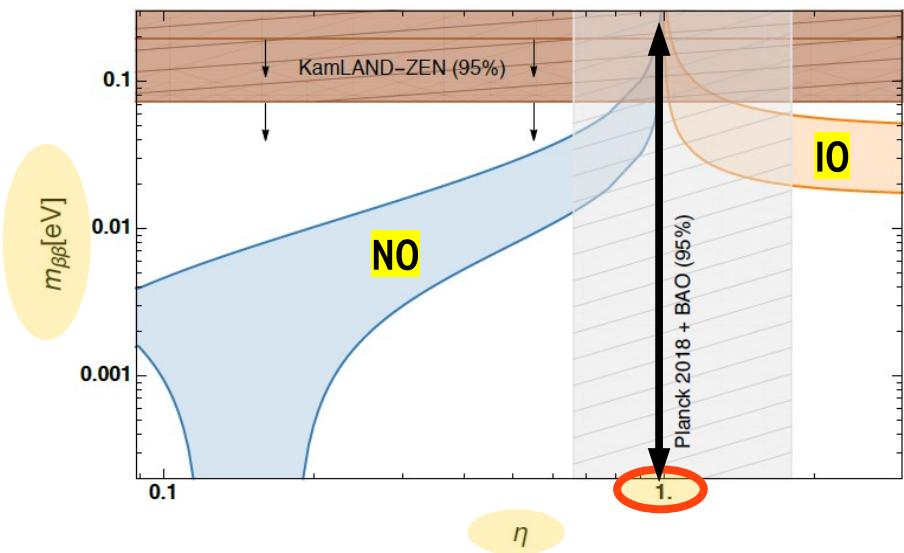


# neutrinoless doublebeta decay

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



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



Nearly degenerate

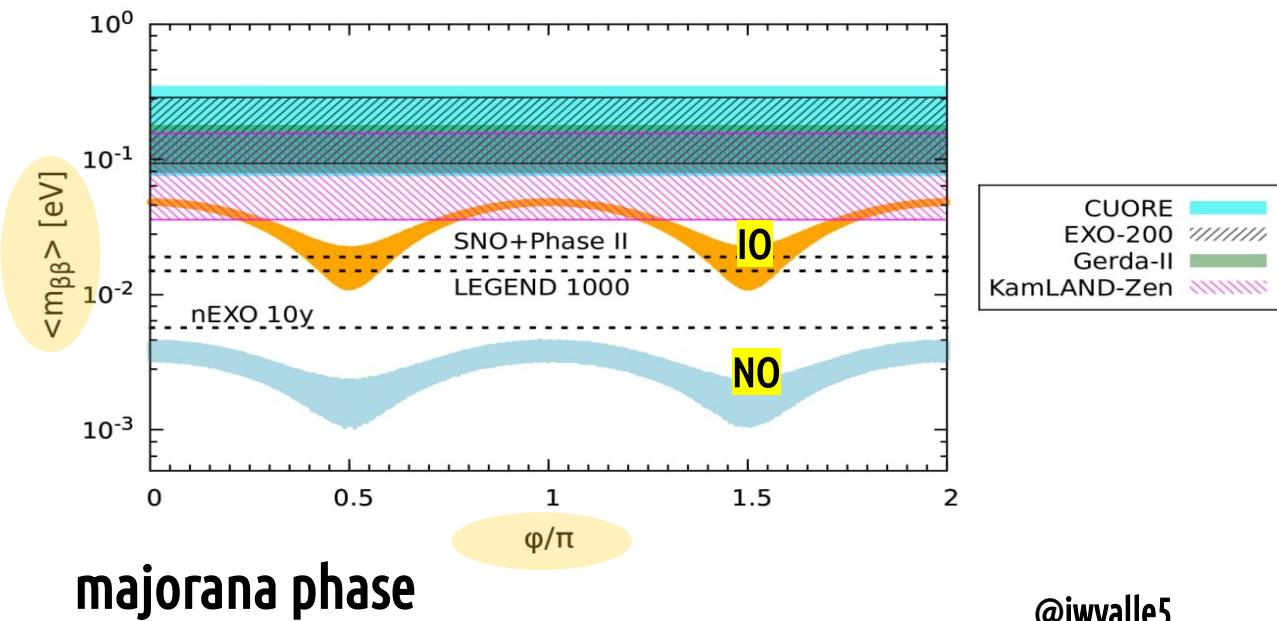
Lattanzi et al JHEP 10 (2020) 213

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

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



## ➤ 3-massive case

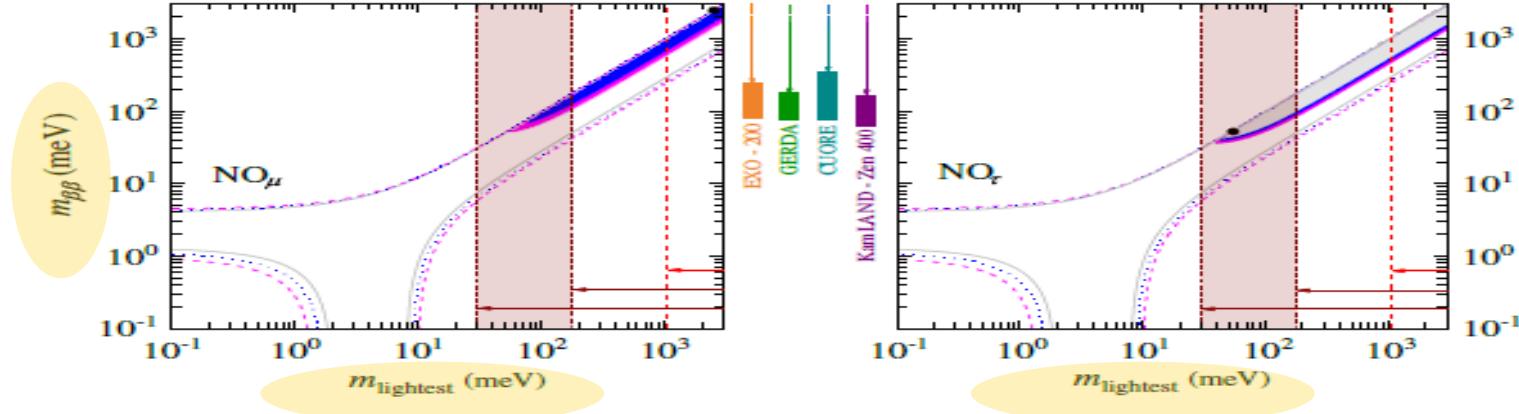
# Lower bounds from family symmetries

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

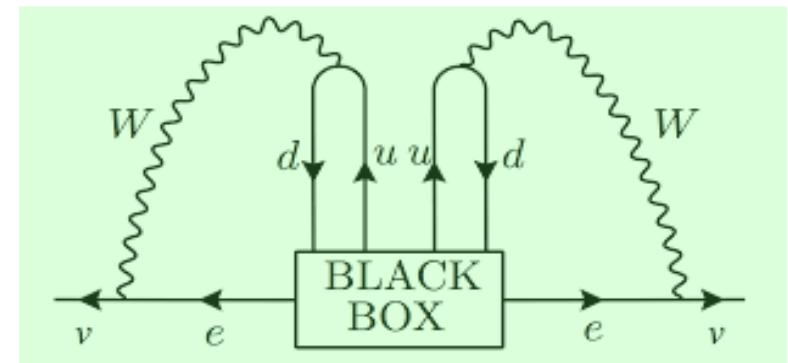


## Significance

Schechter, Valle 1982

Duerr, Lindner, Merle JHEP06(2011)091

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

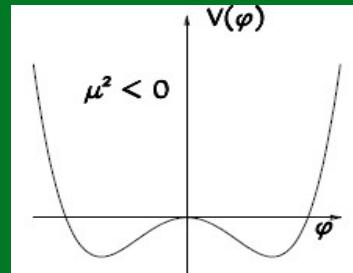


@jwvalle6

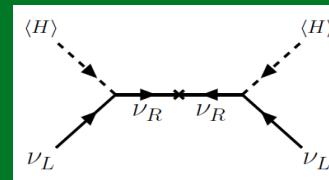
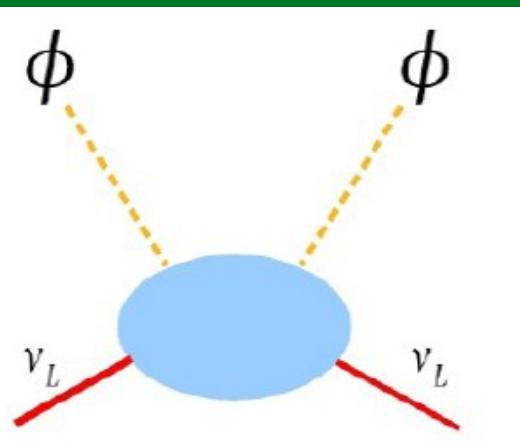
# Origin of neutrino mass stability

## SEESAW dynamics

$$v_3 v_1 \sim v_2^2$$

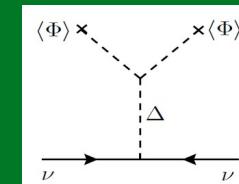


Mandal et al PRD101 (2020) 115030  
JHEP03(2021)212 & JHEP07(2021) 029



### TYPE I

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



### TYPE II

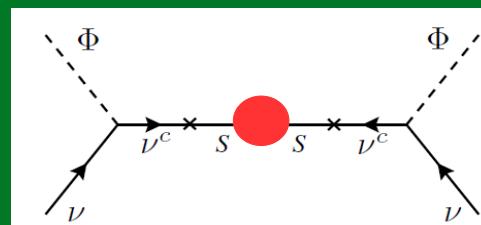
- Schechter-Valle 80 & 82
- Miranda et al PLB829 (2022) 137110
- PRD105 (2022) 095020

**L-R seesaw**      **# of Rs = # Ls (3,3)**  
**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**

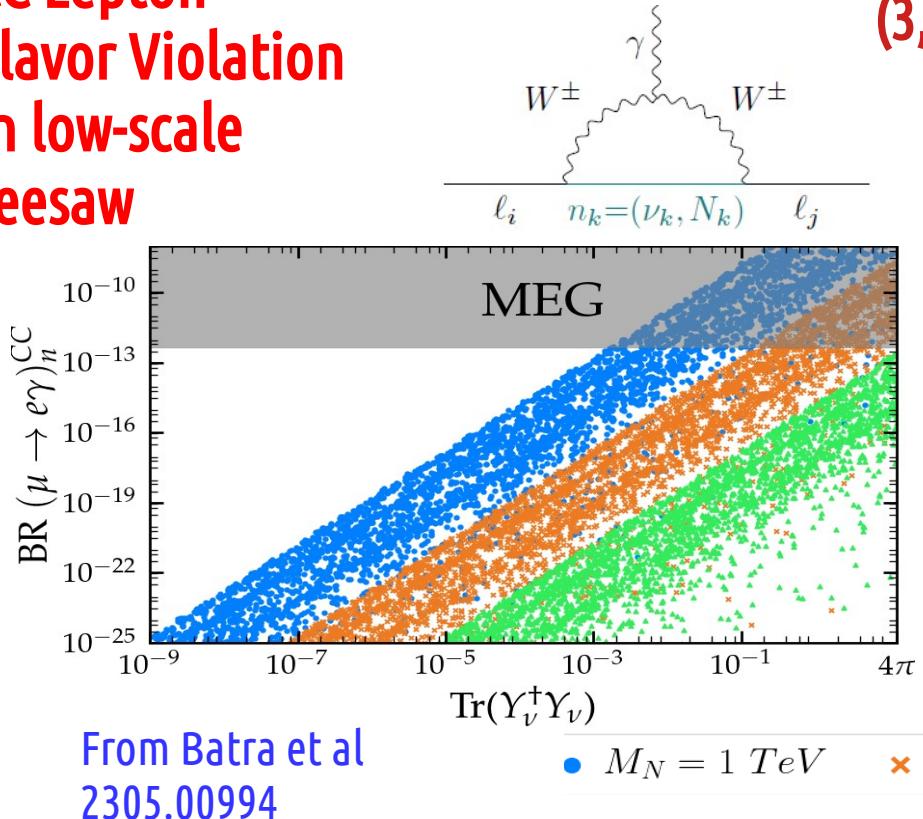


- Mohapatra,Valle 86
- Akhmedov et al Phys.Rev.D53 (1996) 2752
- PhysLettB368 (1996) 270
- Malinsky et al PhysRevLett95(2005)161801

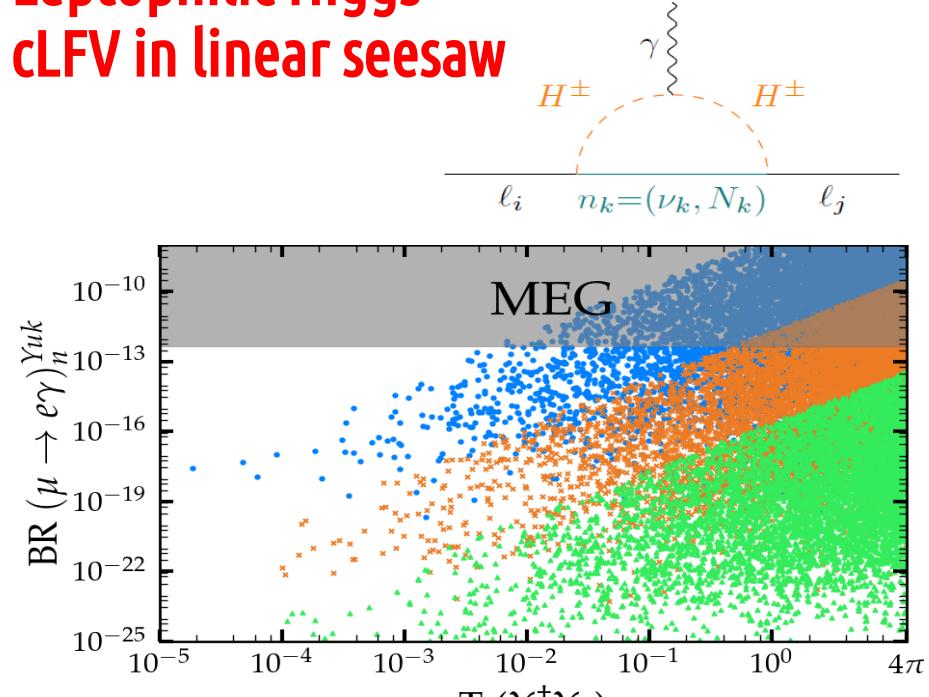
@jwvalle7

# CC Lepton Flavor Violation In low-scale seesaw

(3,6)



# Leptophilic Higgs cLFV in linear seesaw



CLFV persists in the massless limit

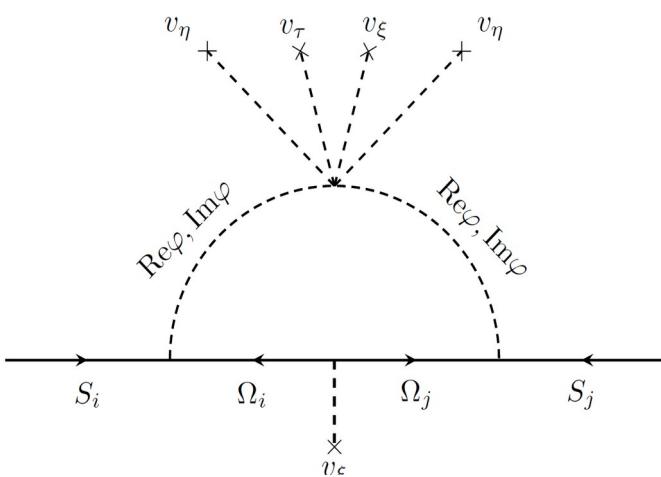
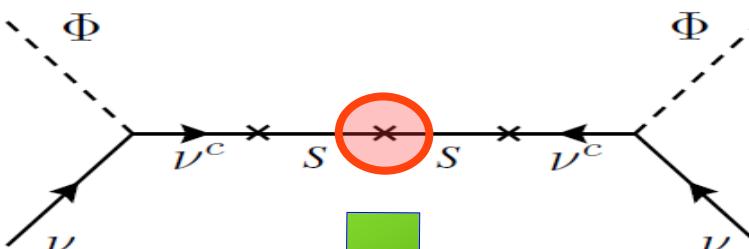
Bernabeu et al B187 (1987) 303-308



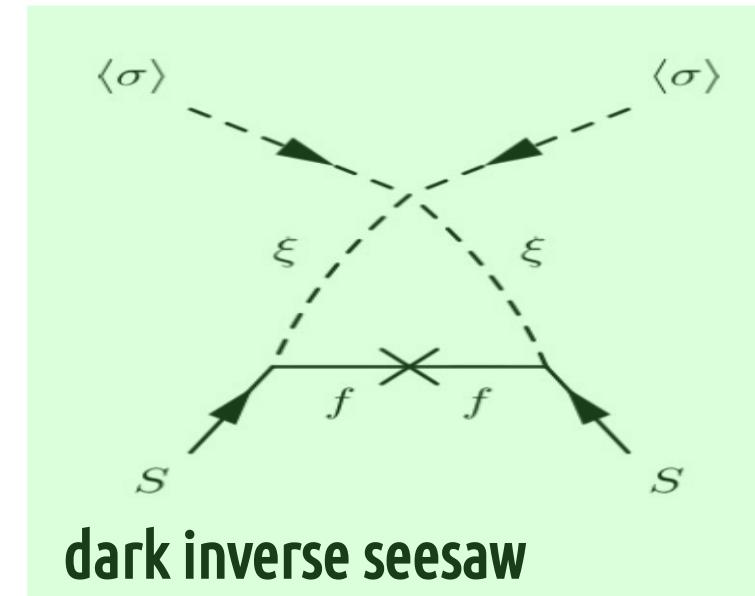
@iwvalle8

# dOubly protected inverse seesaw

(3,6)



radiative  
inverse seesaw



L-R scheme

Cárcamo Hernández et al JHEP 1902 (2019) 065



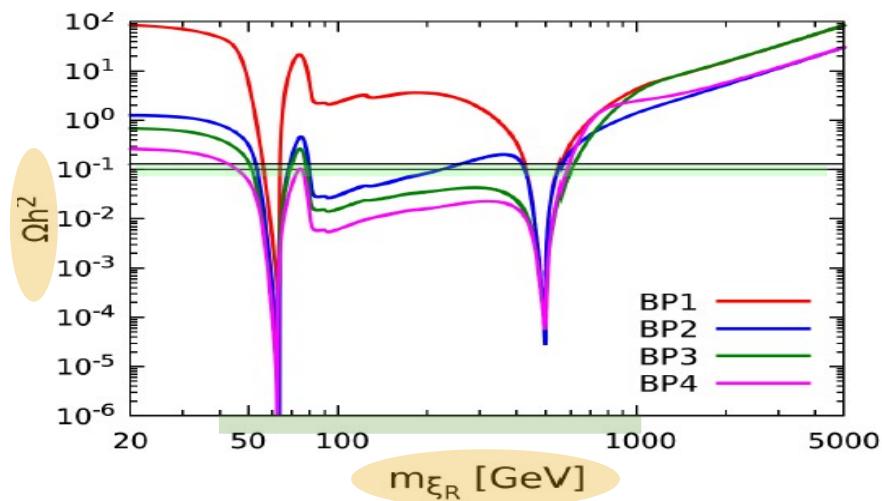
Mandal et al Phys.Lett.B821 (2021) 136609

@jwvalle9

low-scale type-1

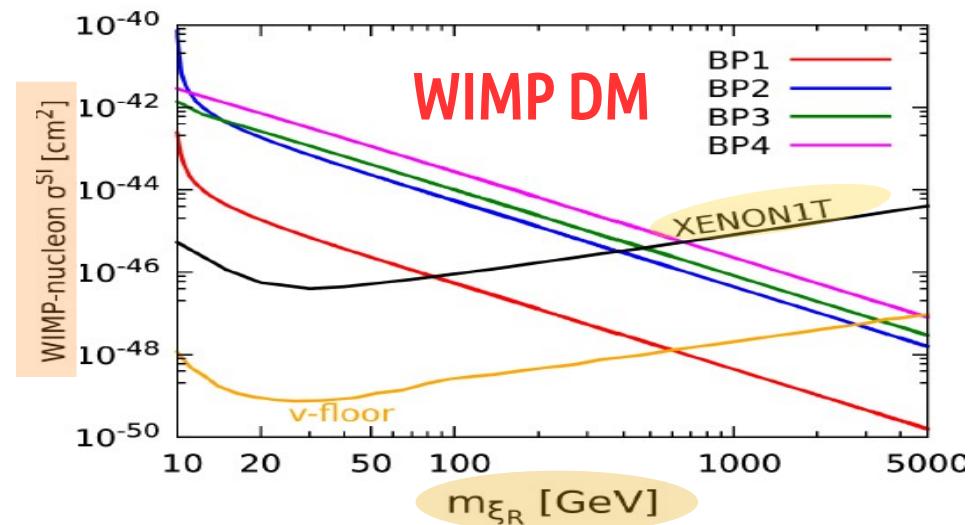
# dark inverse seesaw (3,6)

Lambda $\Lambda$ CDM



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

Xenon1T PhysRevLett.121.111302  
PandaX Lux-Zepellin



With large cLFV effects



@jwvalle10

low-scale type-1

# dark linear seesaw

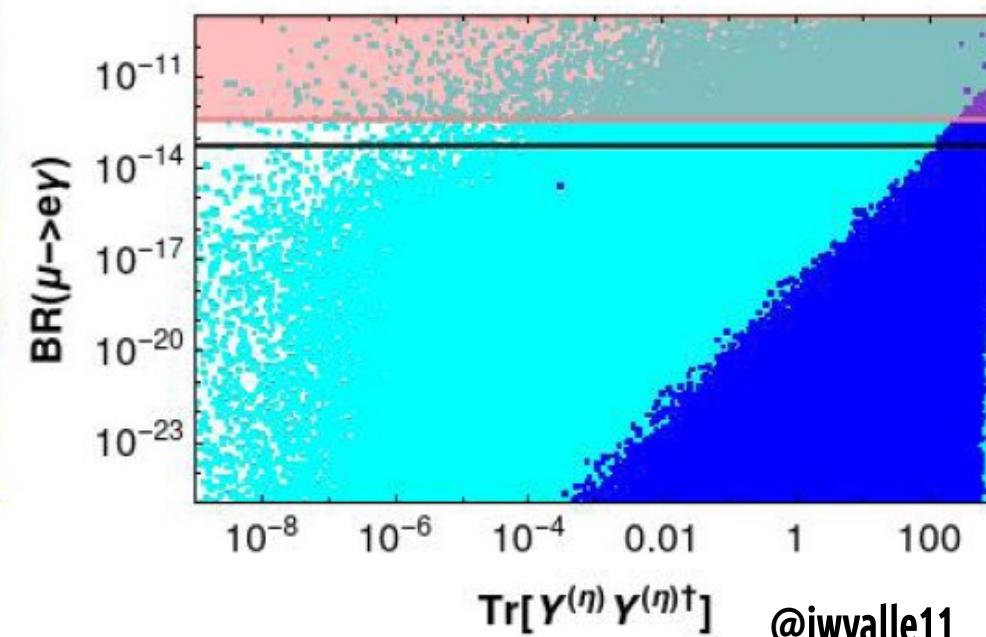
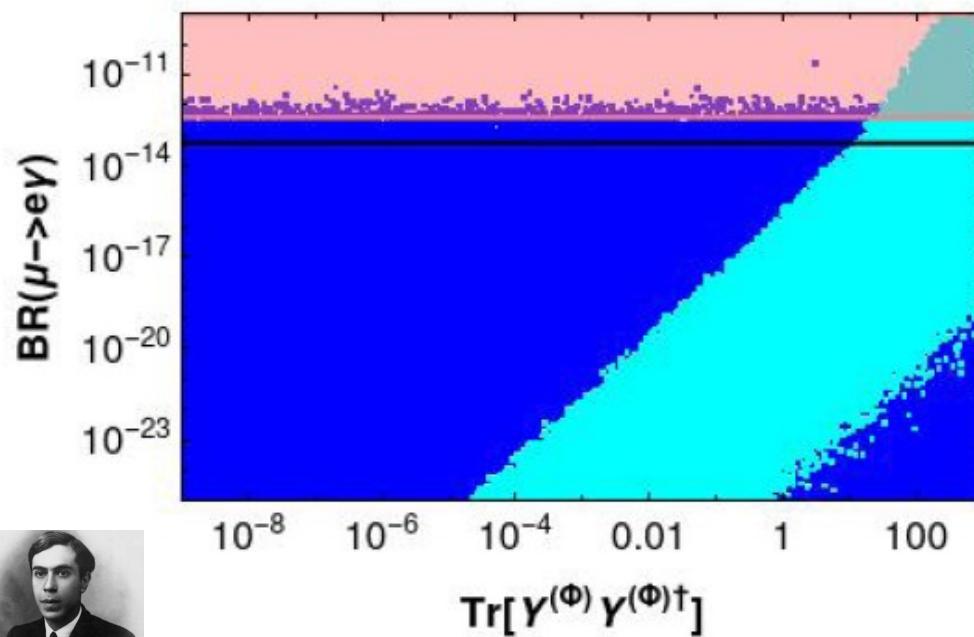
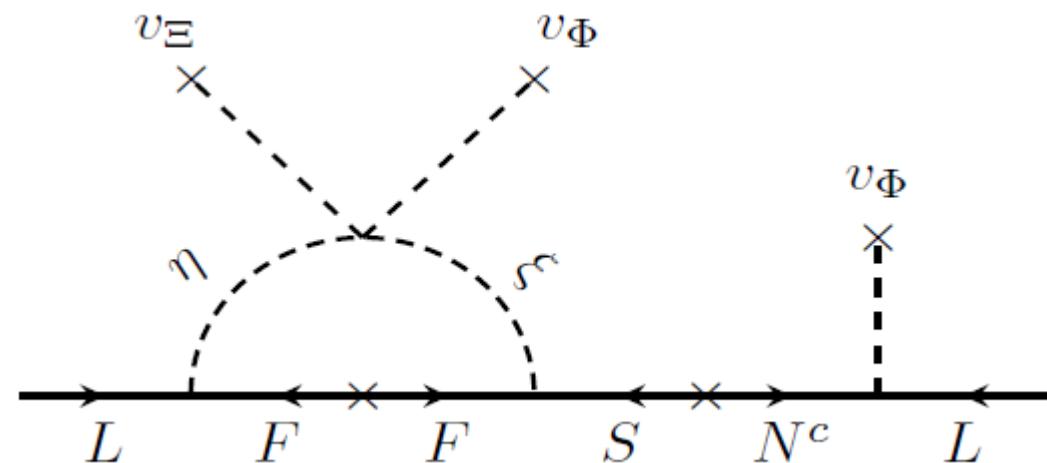
(3,6)

$$M_\nu = \begin{pmatrix} 0_{3 \times 3} & m_D & \varepsilon \\ m_D^T & 0_{3 \times 3} & M \\ \varepsilon^T & M & 0_{3 \times 3} \end{pmatrix}$$

Carcamo, Vishnudath, J.V. 2305.02273

$$m_{\text{light}} = - [m_D M^{-1} \varepsilon^T + \varepsilon M^{-1} m_D^T]$$

(Also Batra, Camara, Joaquim, 2305.01687)



@jwvalle11

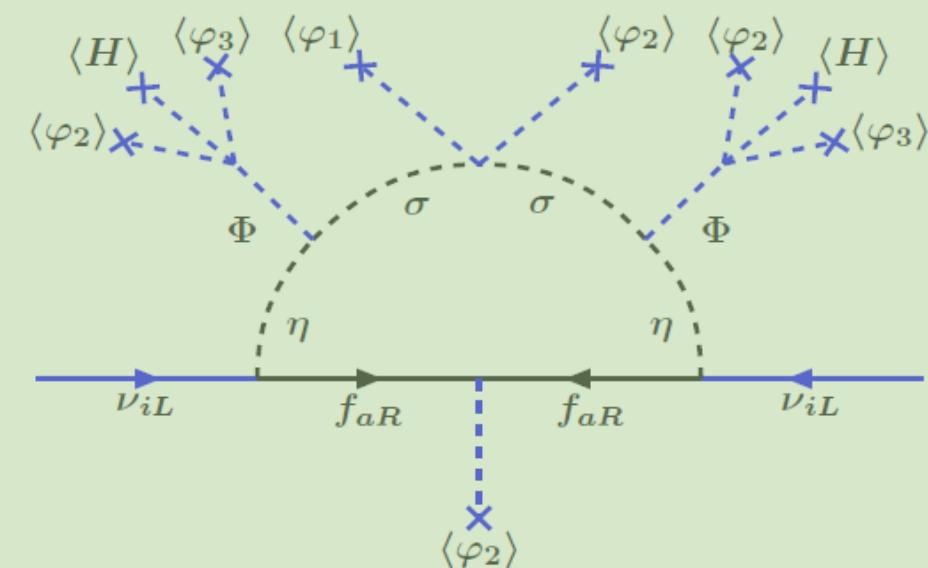
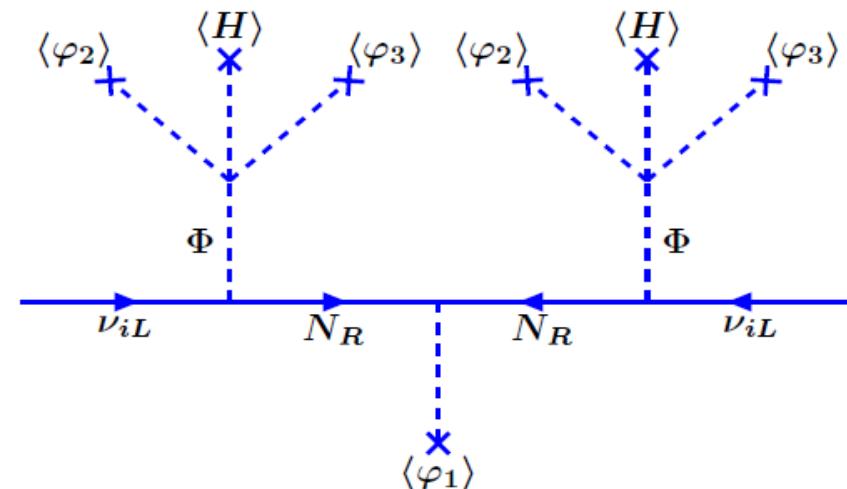
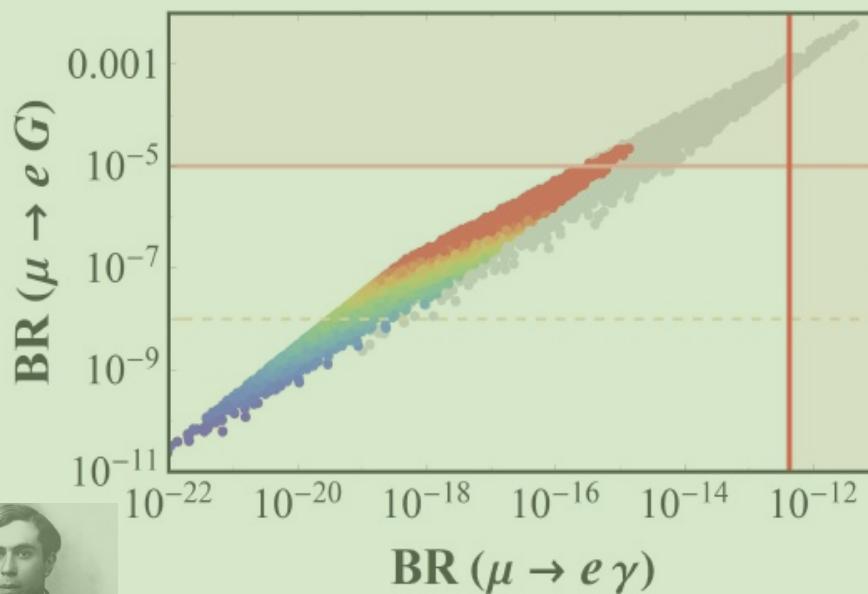
# Lowering the seesaw scale (3,3)

Leite, Sadhukhan, Valle 2307.04840

## SCOTO seesaw

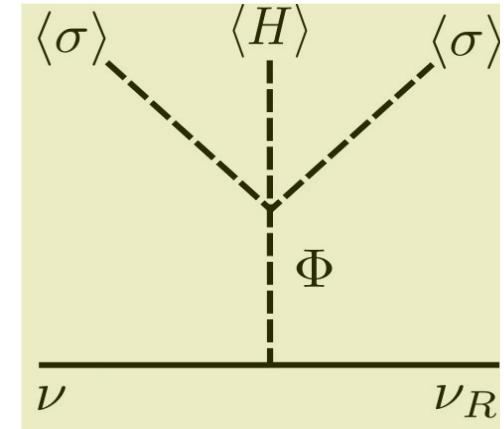
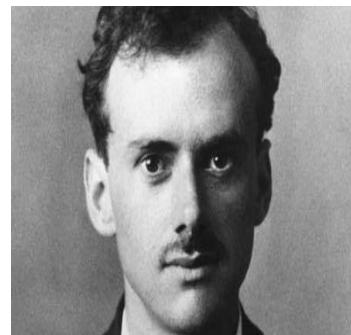
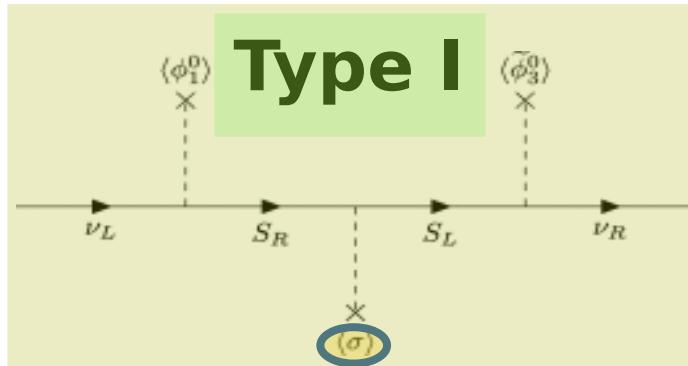
Simplest version in Phys.Lett.B 789 (2019) 132-136  
and Phys.Lett.B 819 (2021) 136458

## dynamical version



$B - L$  charges  $(f_{1R}, f_{2R}, N_R) \sim (-4, -4, 5)$

# seesawing a la



**symmetry protecting small neutrino mass  
+ Diracness**

Peccei-Quinn symmetry

$$m_\nu^D \simeq \frac{y^{\nu_1} (y^S)^{-1} (y^{\nu_2})^T}{\sqrt{2}} \frac{\nu_W}{\nu_\sigma} \begin{matrix} w \\ \sigma \end{matrix}$$

SU3L                                    PQ

Phys.Lett.B 810 (2020) 135829

Phys.Lett. B761 (2016) 431-436

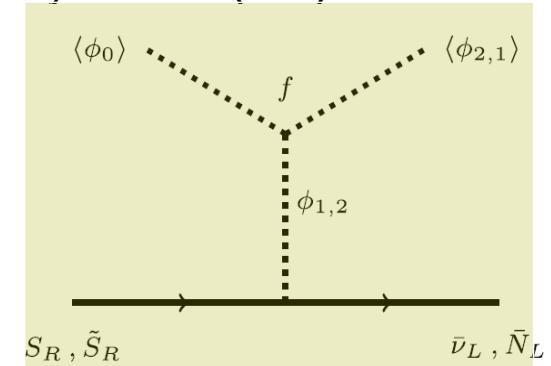
Phys.Lett. B767 (2017) 209-213

Phys.Rev. D98 (2018) 035009

Phys.Lett. B781 (2018) 122-128

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

@jwvalle13

# probing neutrinos at colliders

Geneva

PS

SPS

LHC

27 km

Future  
Circular  
Collider

ILC: 1506.07830, CLIC: 1812.06018,

CEPC: 1811.10545

FCC-ee Eur.Phys.J.ST 228 (2019) 2, 261-623

100 km

low-scale type-2

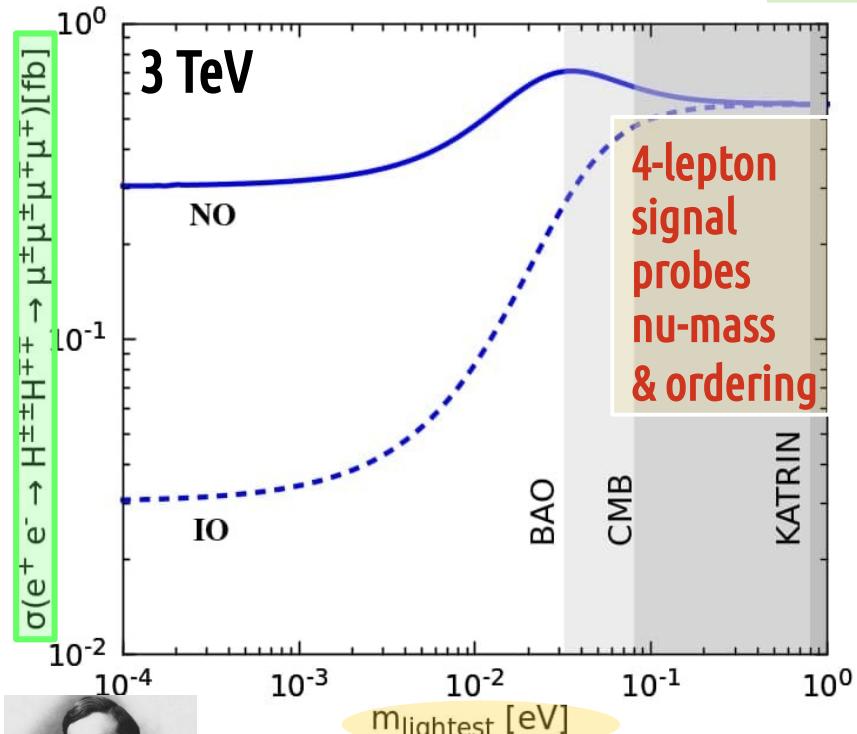
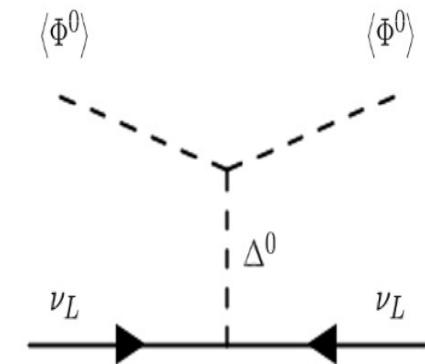
# triplet seesaw

Can be reconstructed from  
data leading to high-  
energy tests

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

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

Miranda et al PLB 829 (2022) 137110

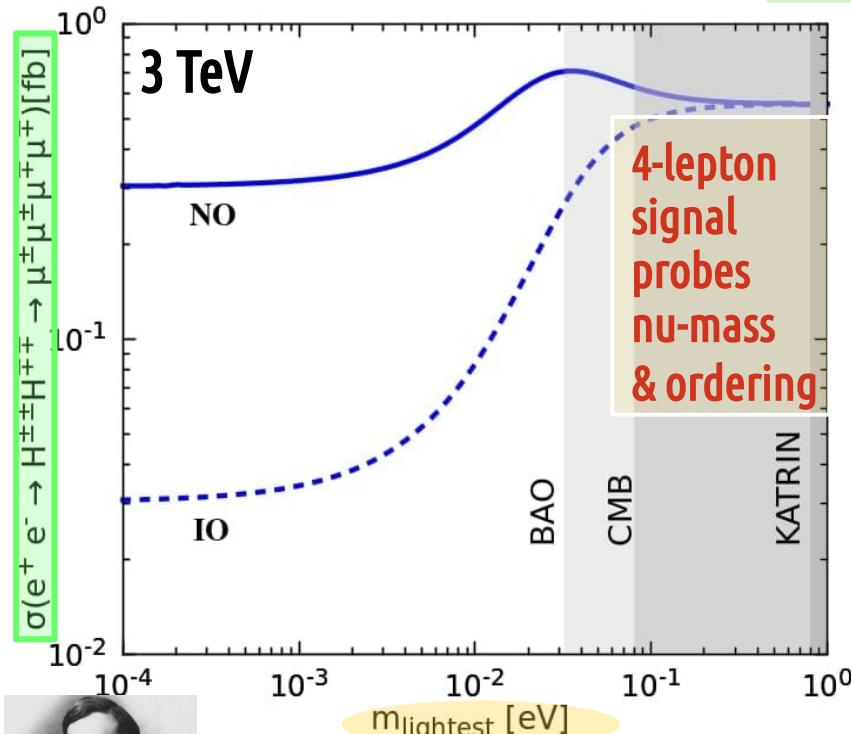


low-scale type-2

# triplet seesaw

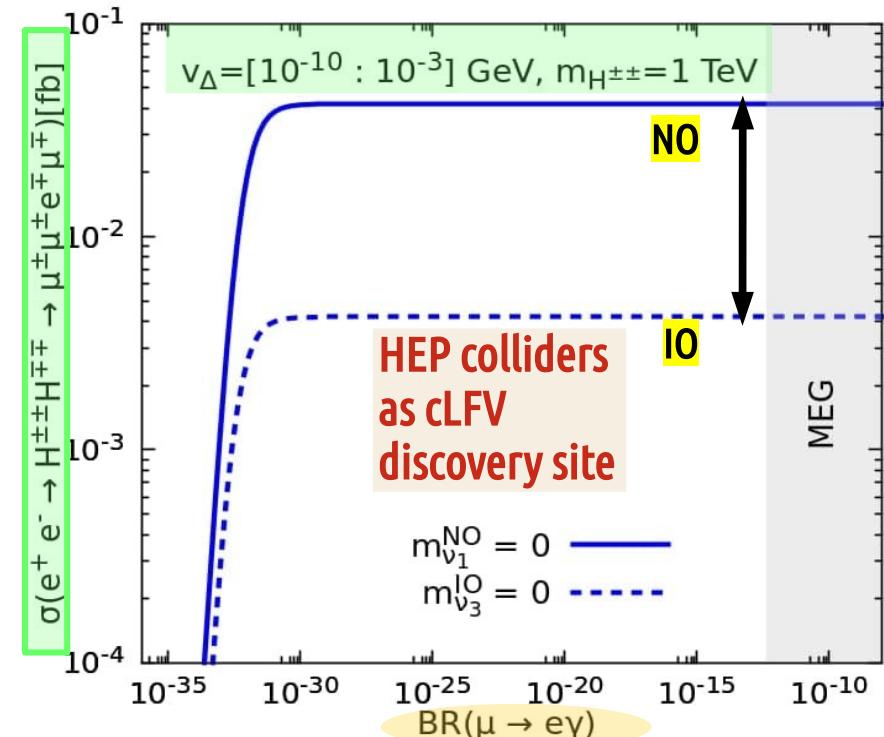
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Miranda et al Phys.Rev.D105 (2022) 095020

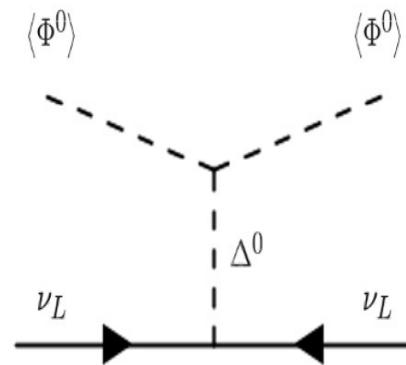


seesaw mediator produced in  
@  $e^+e^- / pp$  collisions

Miranda et al PLB 829 (2022) 137110



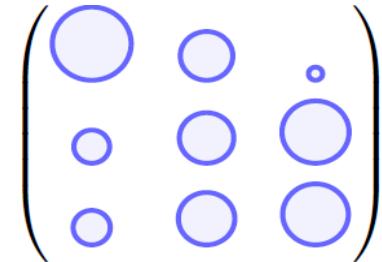
@jwvalle14



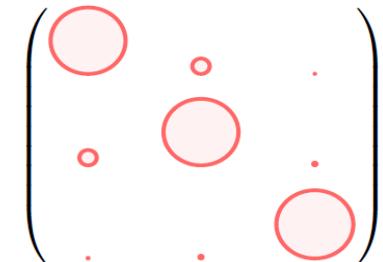


# flavour legacy of oscillations

**Q/L mixing pattern**



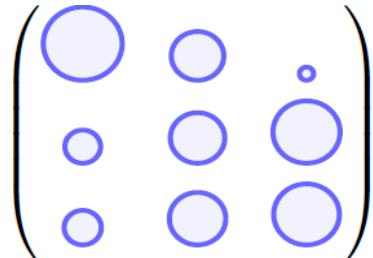
**versus**



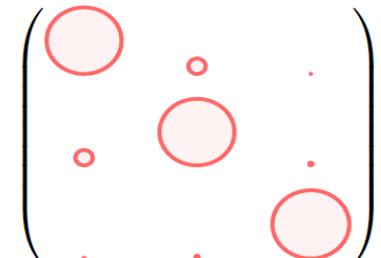


# flavour legacy of oscillations

**Q/L mixing pattern**



**versus**



**Q/L mass hierarchies**

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

from family sym Morisi et al PRD84 (2011) 036003

King et al PLB 724 (2013) 68

Morisi et al PRD88 (2013) 036001

Bonilla et al PLB742 (2015) 99

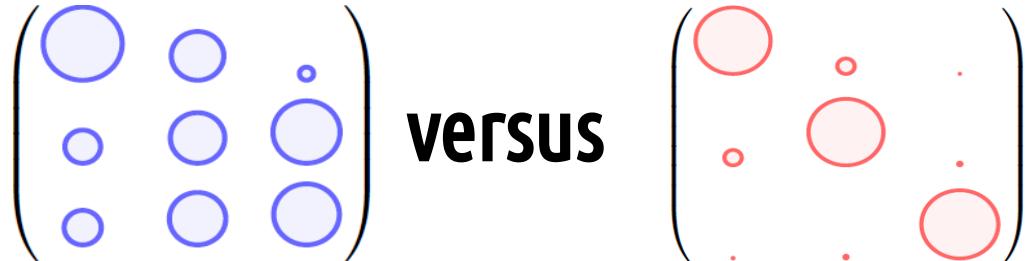
from PQ sym Reig, JV, Wilczek PRD98 (2018) 095008

from orbifolds De Anda et al PRD105 (2022) 055030 ,  
JHEP10 (2020) 190, PLB 801 (2020) 135195  
PRD 101 (2020) 11, 116012 and 2212.09174



# flavour legacy of oscillations

## Q/L mixing pattern



## Q/L mass hierarchies

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from family sym Morisi et al PRD84 (2011) 036003

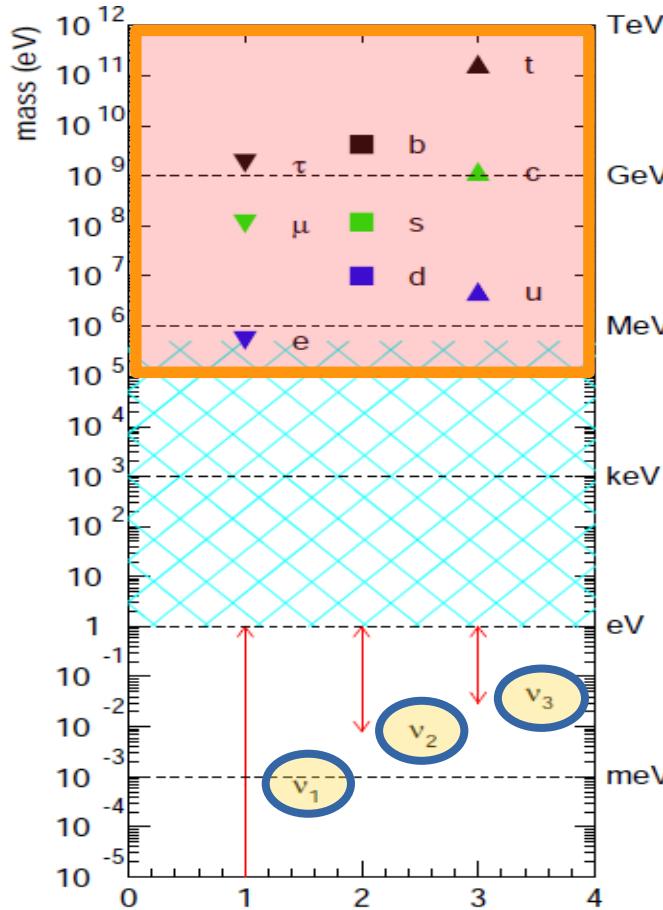
King et al PLB 724 (2013) 68

Morisi et al PRD88 (2013) 036001

Bonilla et al PLB742 (2015) 99

from PQ sym Reig, JV, Wilczek PRD98 (2018) 095008

from orbifolds De Anda et al PRD105 (2022) 055030 ,  
JHEP10 (2020) 190, PLB 801 (2020) 135195  
PRD 101 (2020) 11, 116012 and 2212.09174



a more radical departure?

# 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 !



the neutrino revolution

Oscillation discovery  
brought neutrinos to  
the spotlight

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

Collider imprints of neutrino completions  
neutrinos and flavor / cLFV / LNV  
neutrinos and dark matter  
neutrinos and strong CP problem  
neutrinos and unification  
neutrinos and SM anomalies @jwvalle16

# Back-ups