completing the standard model

JOSÉ W F VALLE

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Astroparticles and High Energy Physics Group

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GOBIERNO DE ESPAÑA
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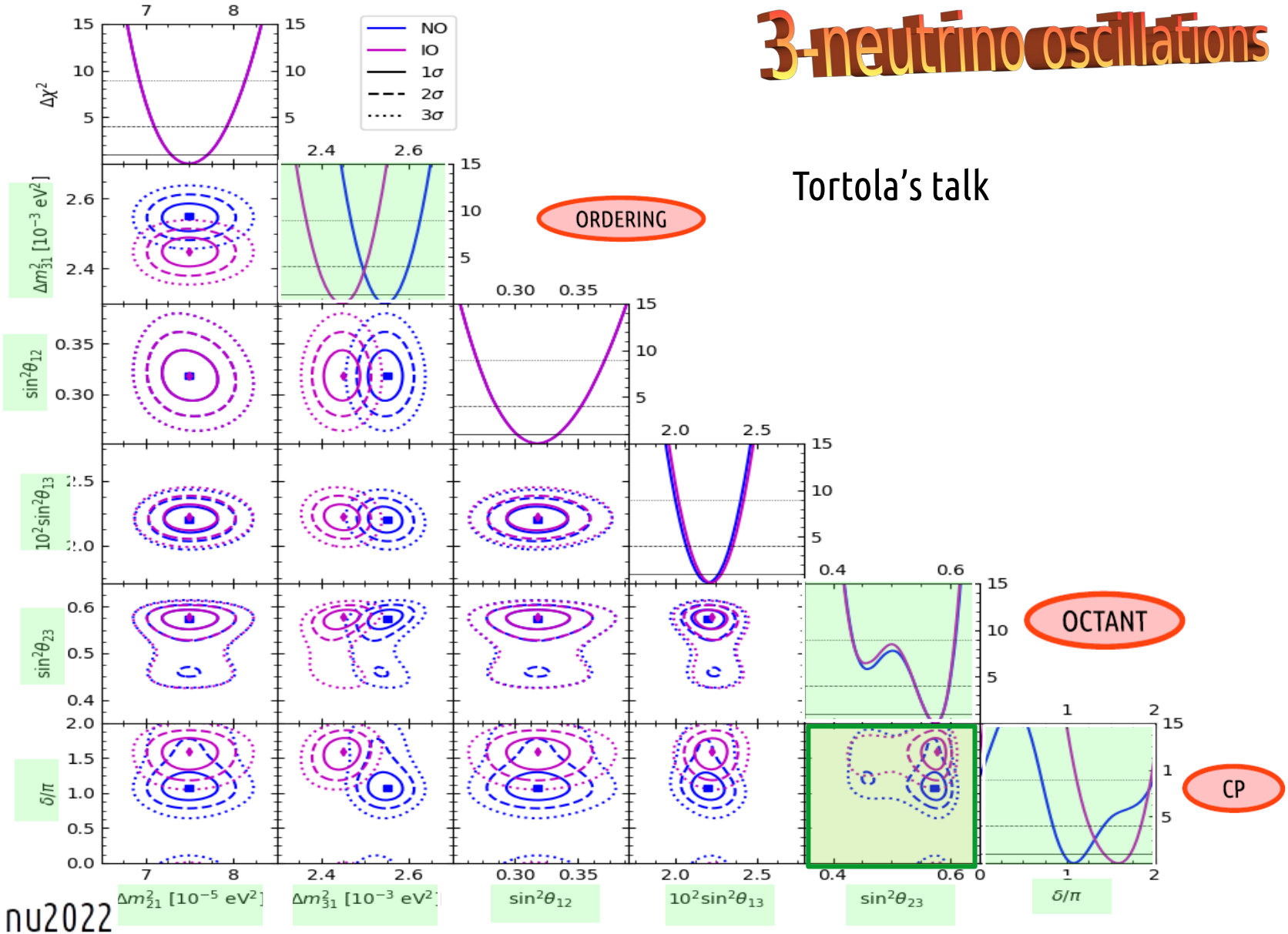
GENERALITAT VALENCIANA
Conselleria d'Educació, Investigació, Cultura i Esport

FLASY 2022 | 9th Workshop on Flavour Symmetries and Consequences in Accelerators and Cosmology

June 27 - July 1, 2022
IST Congress Centre, Instituto Superior Técnico
Lisbon, Portugal

Organised by Centro de Física Teórica de Partículas (CFTP)

3-neutrino oscillations



Tortola's talk

PF de Salas et al JHEP02(2021)071

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

Updates from nu2022

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

@jwvalle2

DUNE
Hyper-K

Leptonic CPV reviews

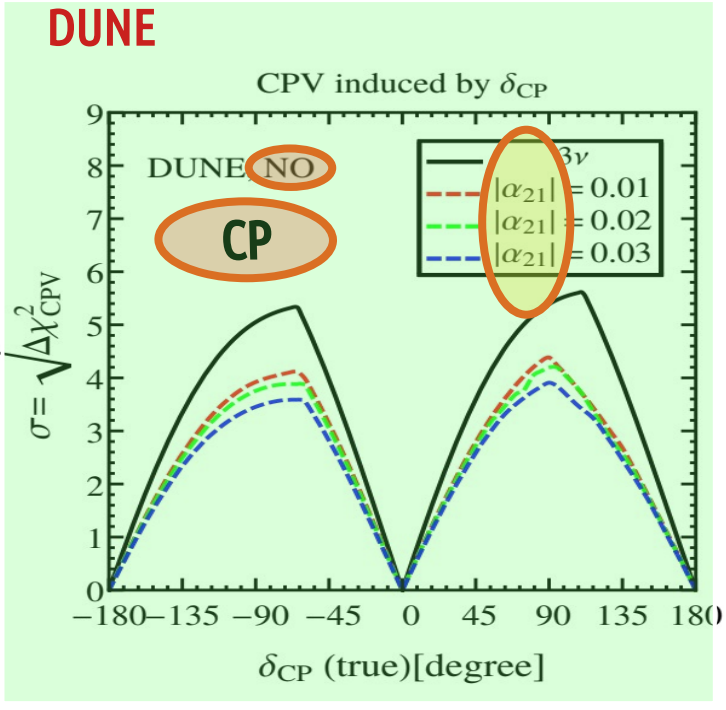
Nunokawa, Parke, JV

Prog.Part.Nucl.Phys. 60 (2008) 338

Branco, Felipe, Joaquim,

Rev.Mod.Phys. 84 (2012) 515

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

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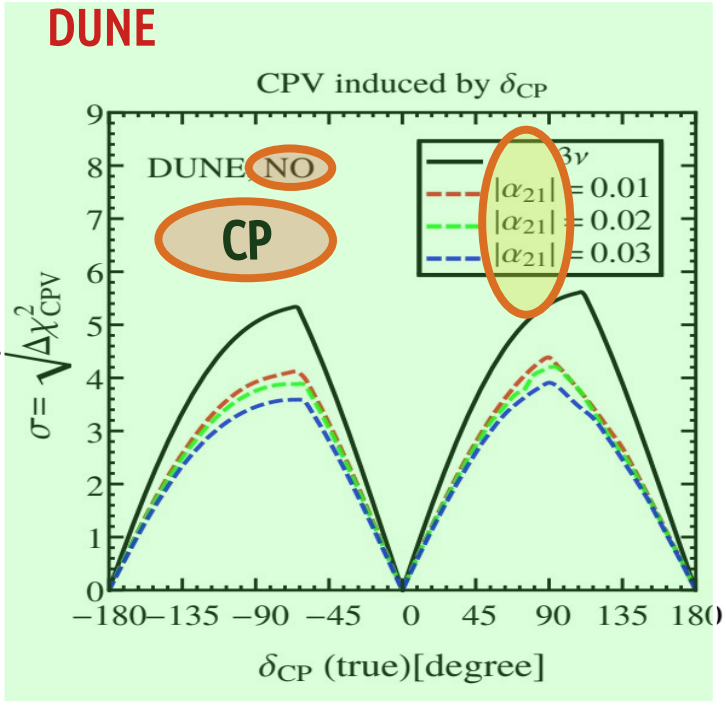

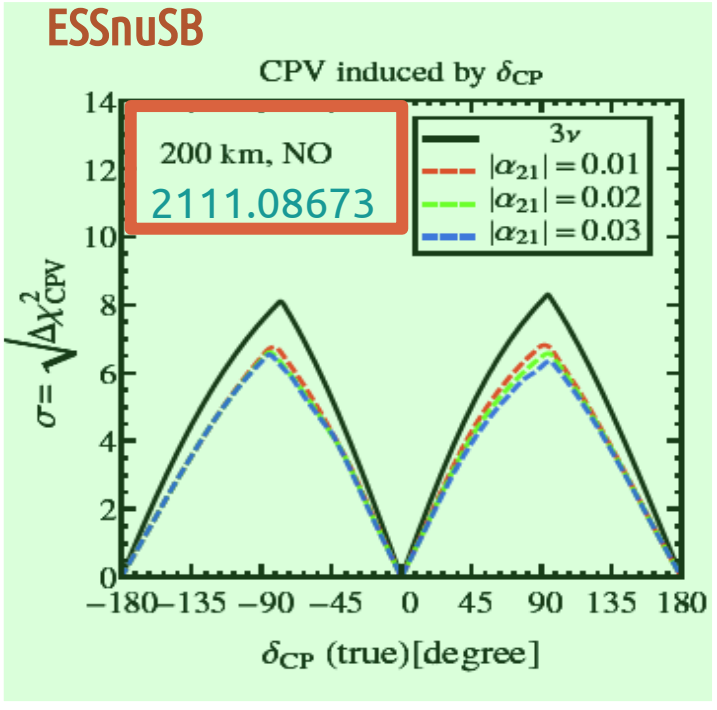

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@jwvalle3

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

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

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θ_{13} ⇒ CP

Phys.Rev.D98(2018)055019

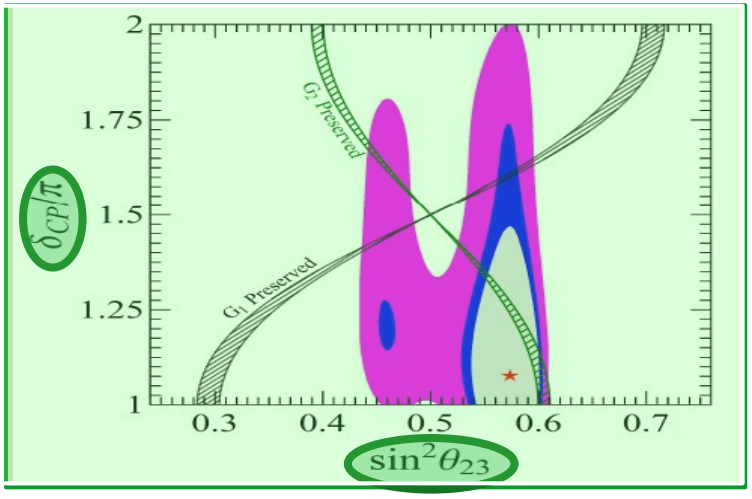
$$\sin^2\theta_{12}\cos^2\theta_{13} = \frac{1}{3}$$

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

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

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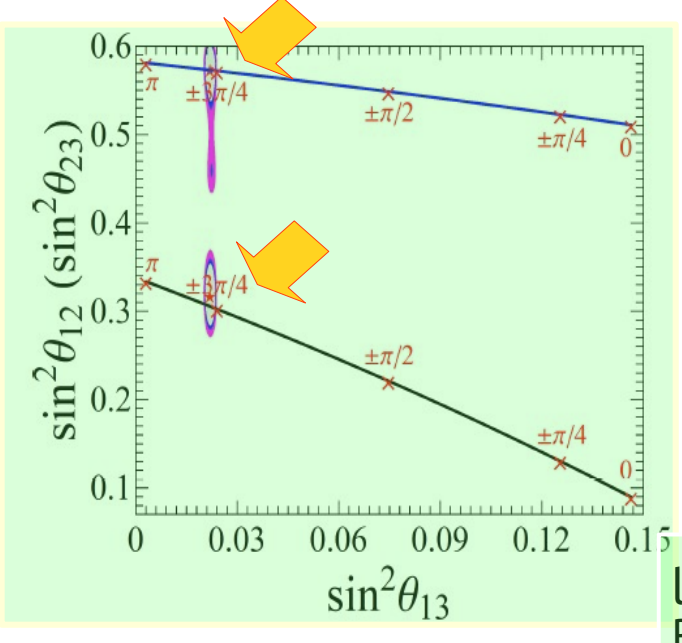


looser realization
Phys.Lett.B 796 (2019) 162

From Phys.Lett. B792 (2019) 461

Many other patterns, e.g. trimaximal, most can be probed at DUNE

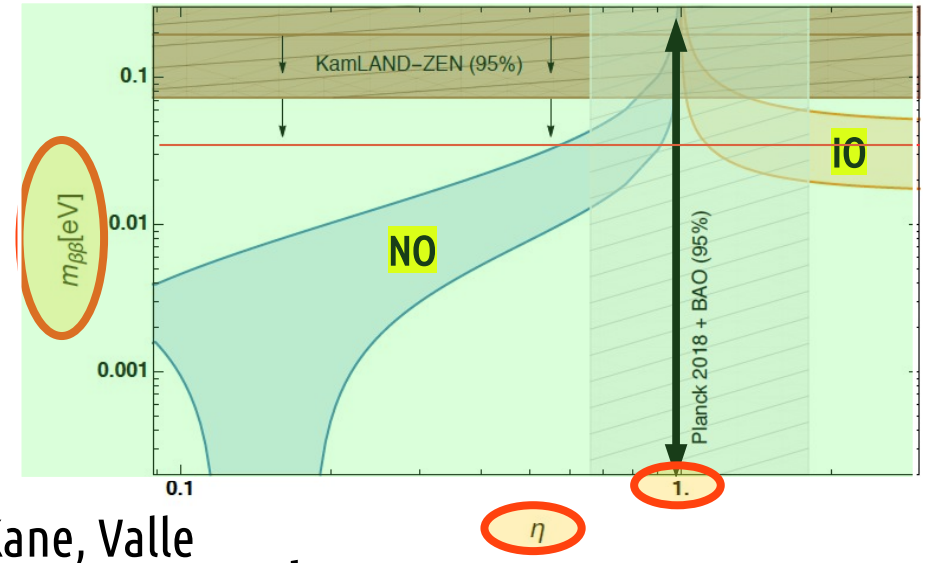
e.g. Phys.Rev.D97(2018)095025

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

- **Quasi-degenerate strongly-disfavored**



Lattanzi, Gerbino, Freese, Kane, Valle
JHEP 10 (2020) 213

degeneracy parameter

neutrinoless doublebeta decay

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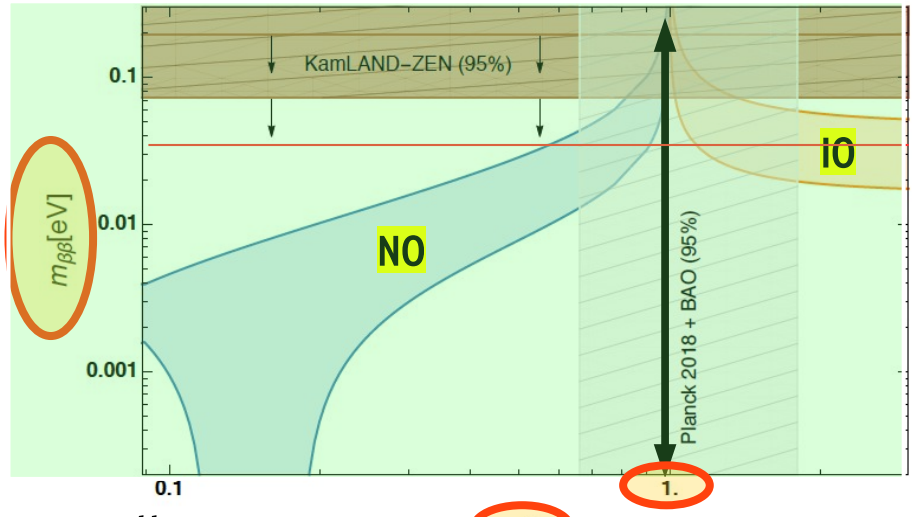


- **Quasi-degenerate strongly-disfavored**

Lattanzi, Gerbino, Freese, Kane, Valle
JHEP 10 (2020) 213

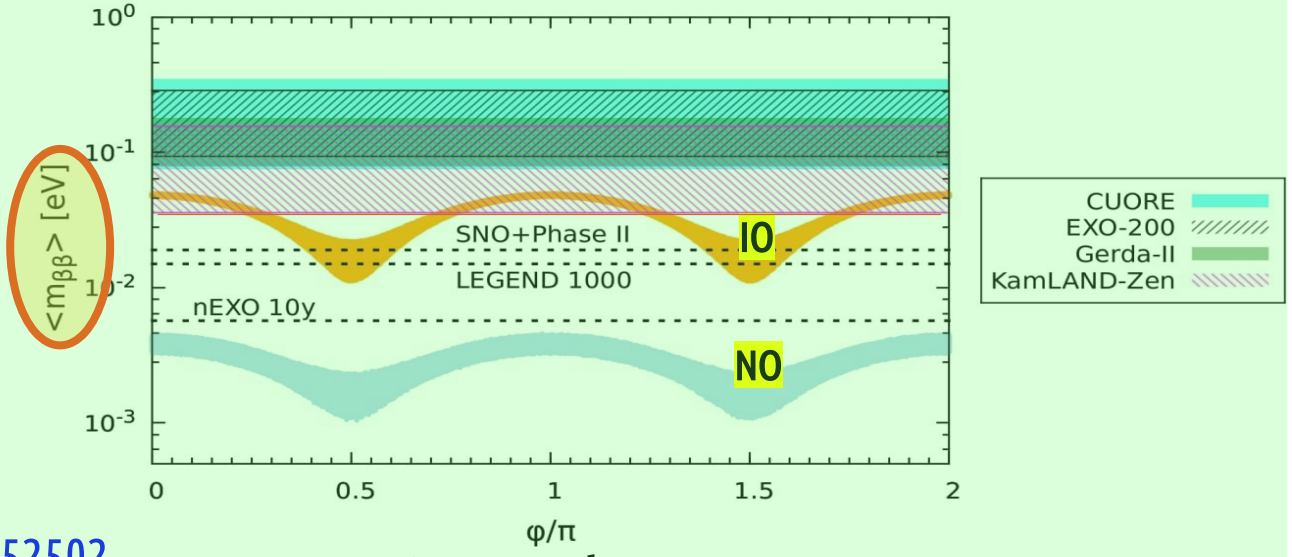
- **One-massless neutrino**

Reig et al Phys.Lett. B790 (2019)303

Barreiros, Felipe & Joaquim JHEP01 (2019) 223

Mandal et al PLB789 (2019) 132

Avila et al Eur.Phys.J.C 80 (2020) 10, 908

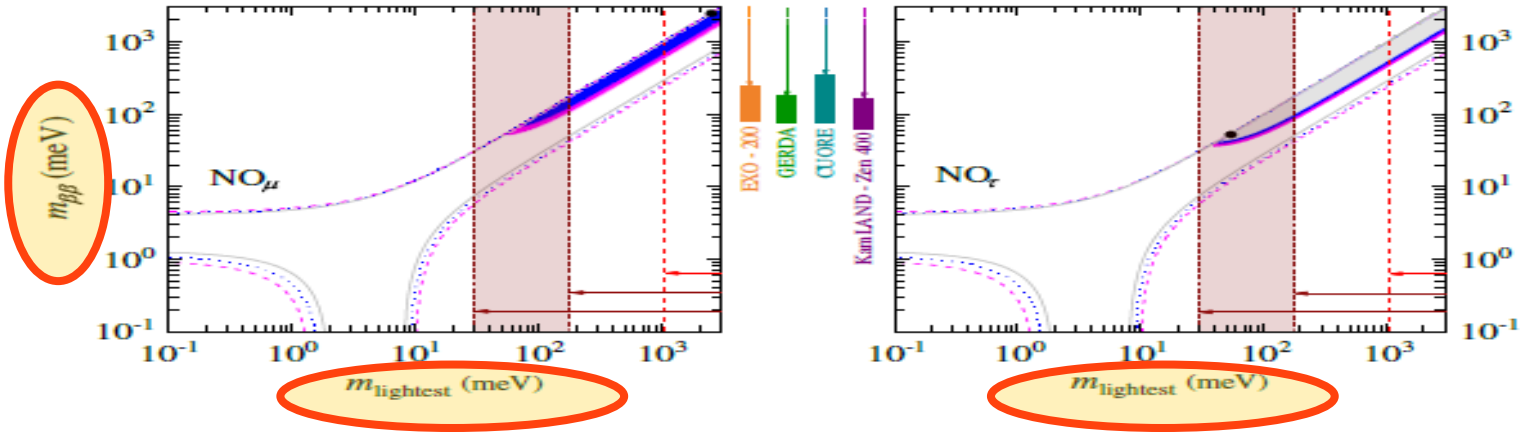


Agostini et al. Science 365 (2019) 1445
Final Gerda Phys.Rev.Lett. 125(2020) 252502

➢ **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

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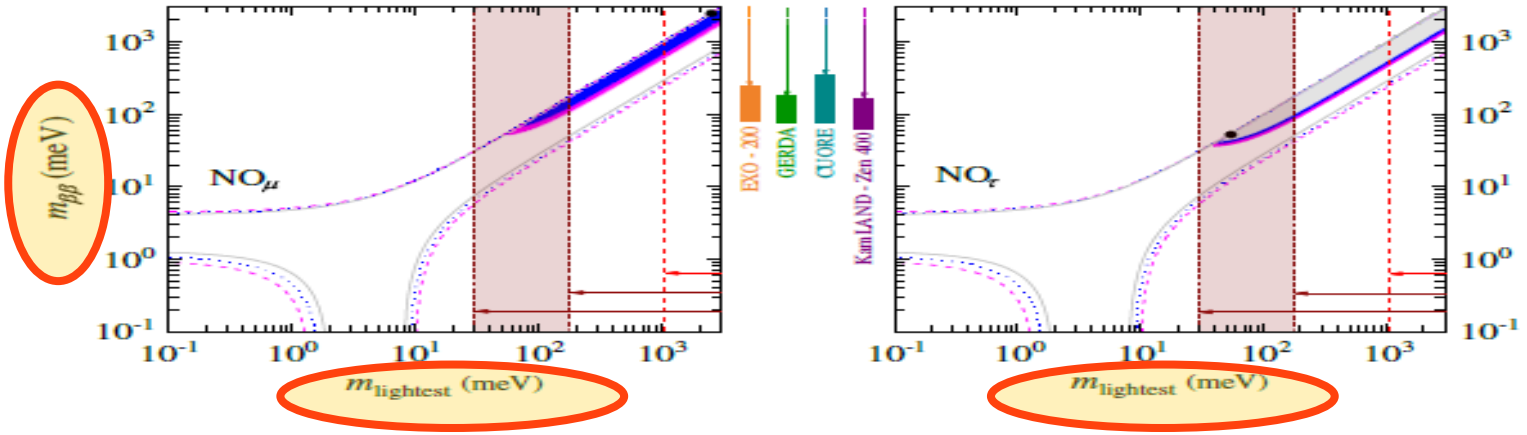
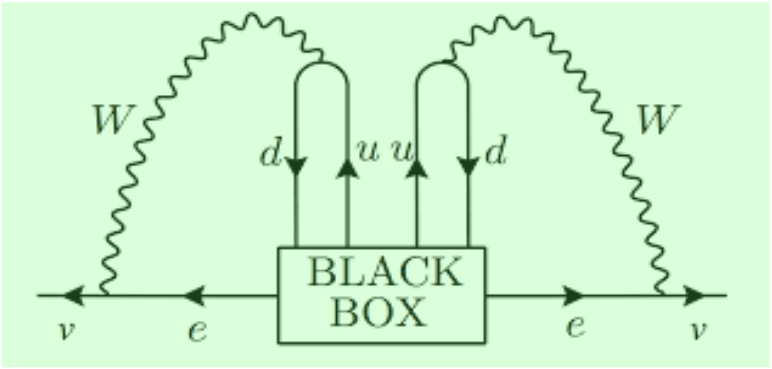
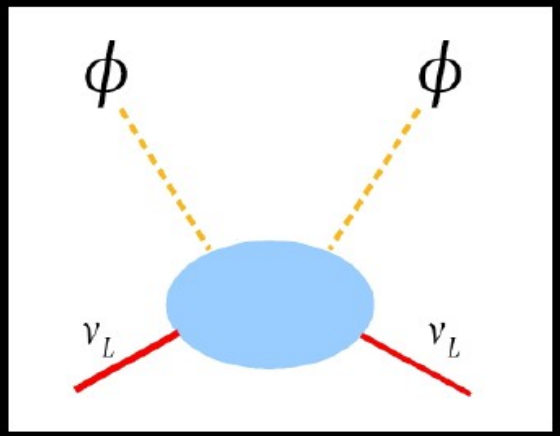


From Barreiros et al JHEP04(2021)249

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

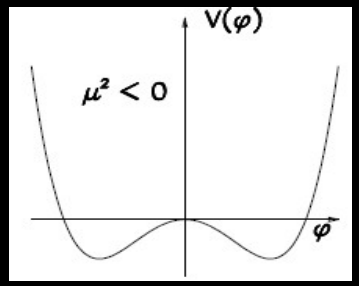


Origin of neutrino mass



Origin of neutrino mass

stability

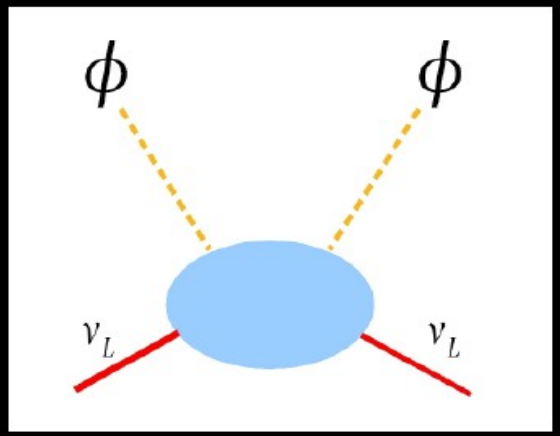


SEESAW dynamics

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

Phys.Rev.D 101 (2020) 115030

JHEP03(2021)212 & JHEP07(2021) 029



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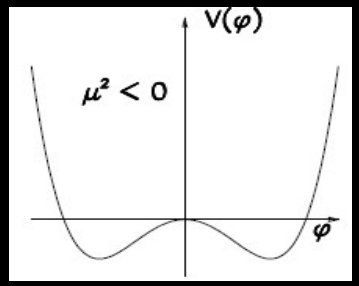

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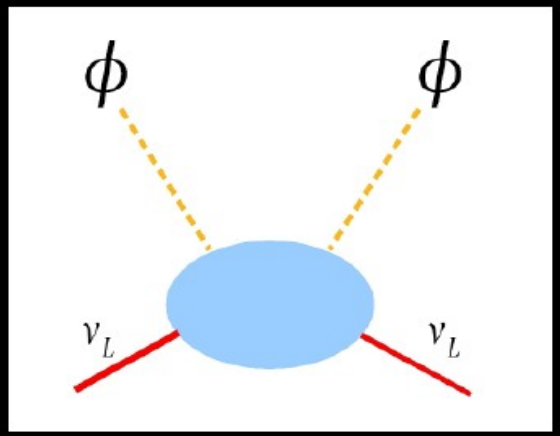
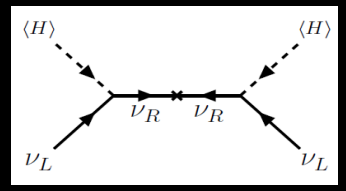
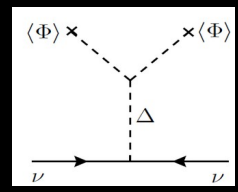




TYPE I

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



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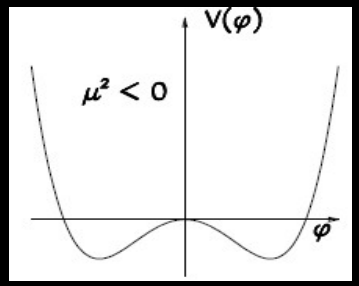

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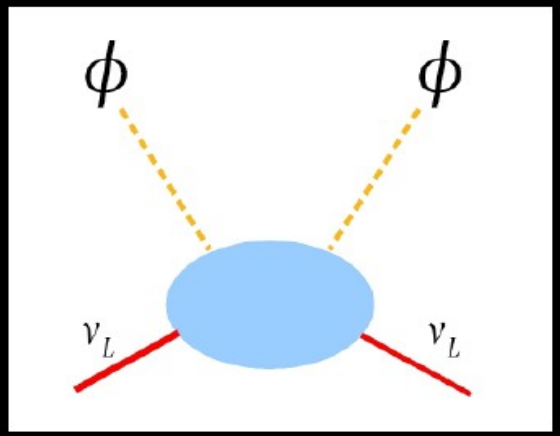

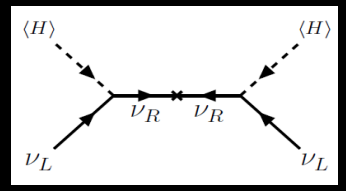

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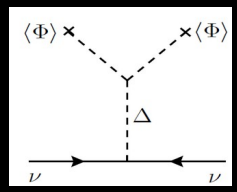

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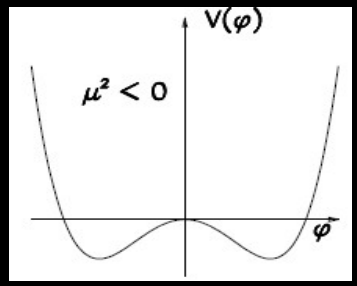
Origin of neutrino mass

stability



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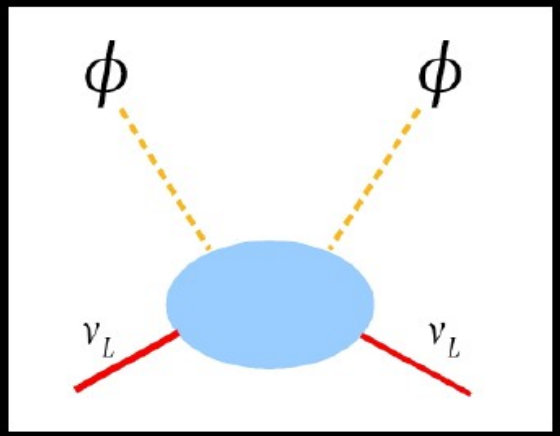

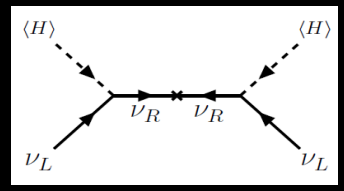

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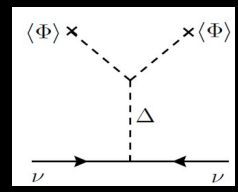

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- **MISSING PARTNER**

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

$m_{\beta\beta}$

Origin of neutrino mass

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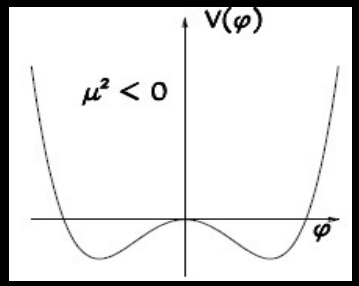

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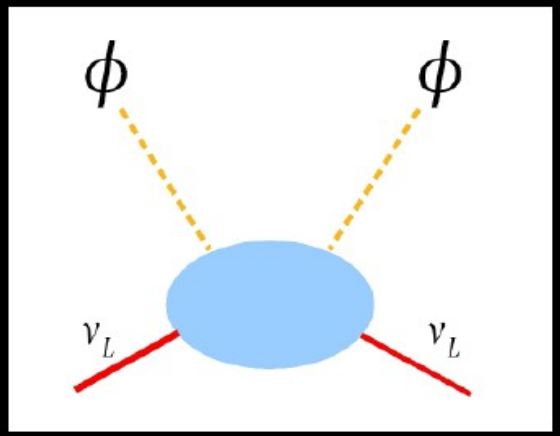

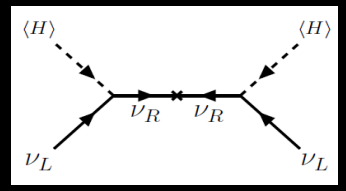

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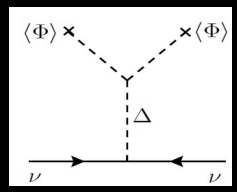

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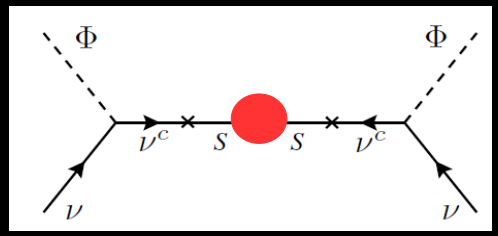
- **MISSING PARTNER** **(3,2)** min viable type1 seesaw
  (3,1) **scoto-seesaw** template

$m_{\beta\beta}$

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

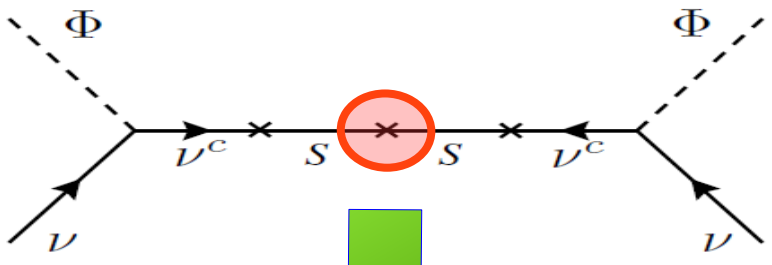


Mohapatra,Valle 86

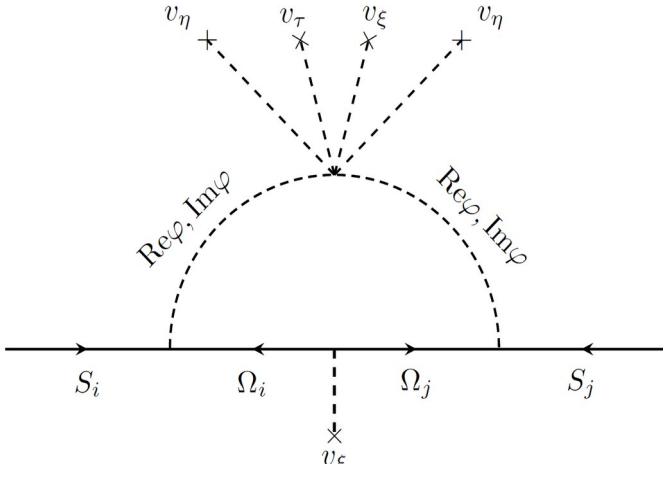
Akhmedov et al Phys.Rev.D53 (1996) 2752
PhysLettB368 (1996) 270

Malinsky et al PhysRevLett95(2005)161801

doubly protected inverse seesaw

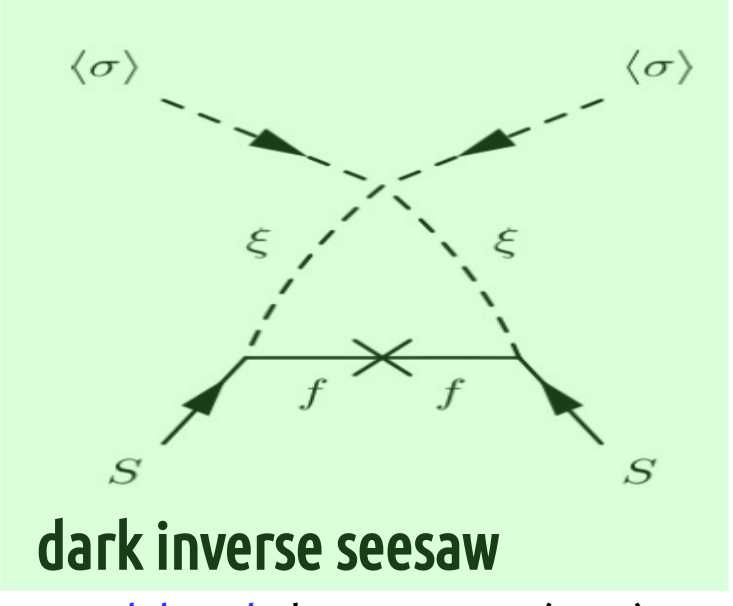


radiative
inverse seesaw



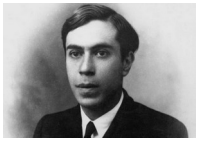
L-R scheme

:Cárcamo Hernández et al JHEP 1902 (2019) 065



dark inverse seesaw

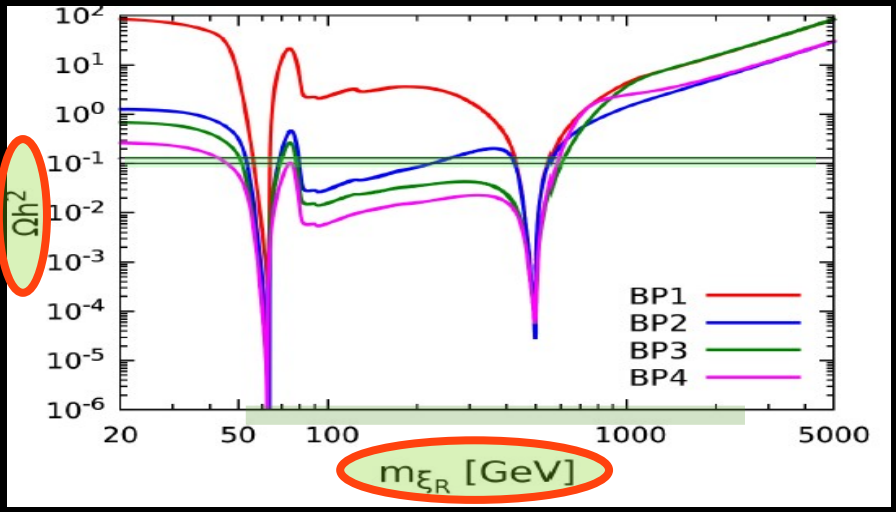
Mandal et al Phys.Lett.B821 (2021) 136609



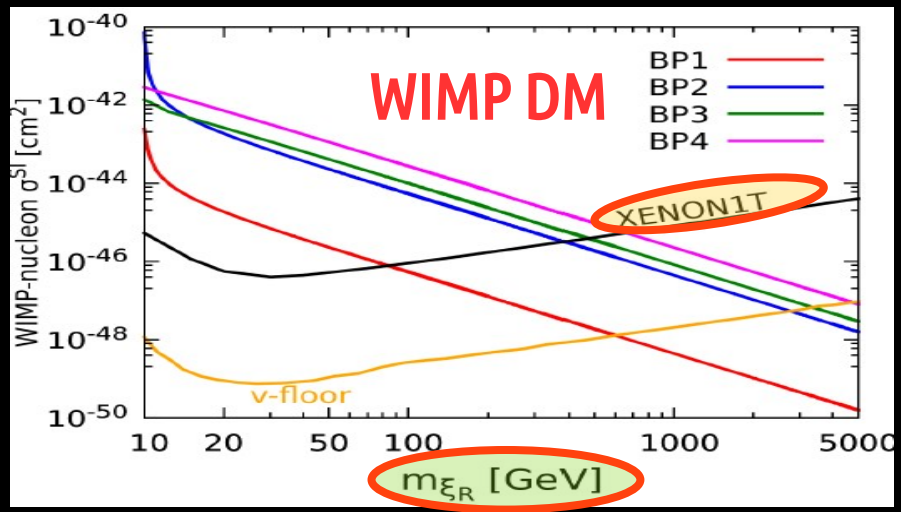
dark inverse typeI seesaw mechanism

LambdaCDM

Phys.Lett.B 821 (2021) 136609



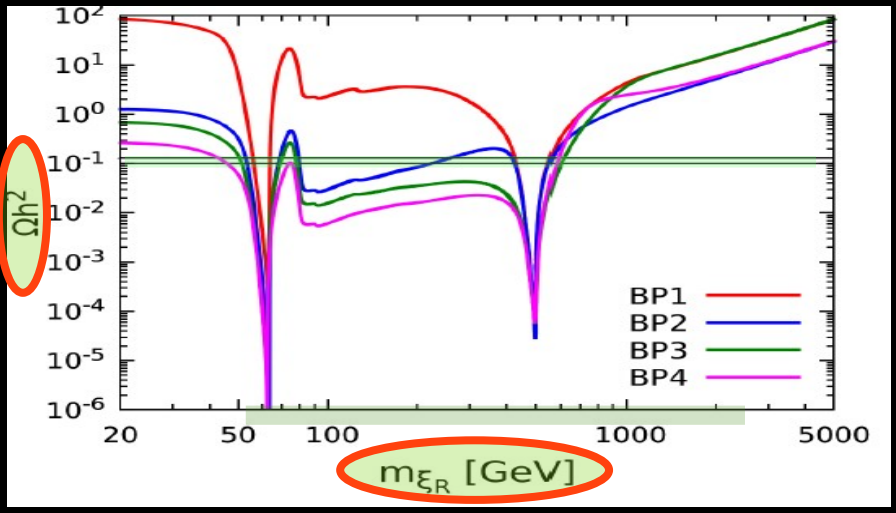
Xenon1T PhysRevLett.121.111302



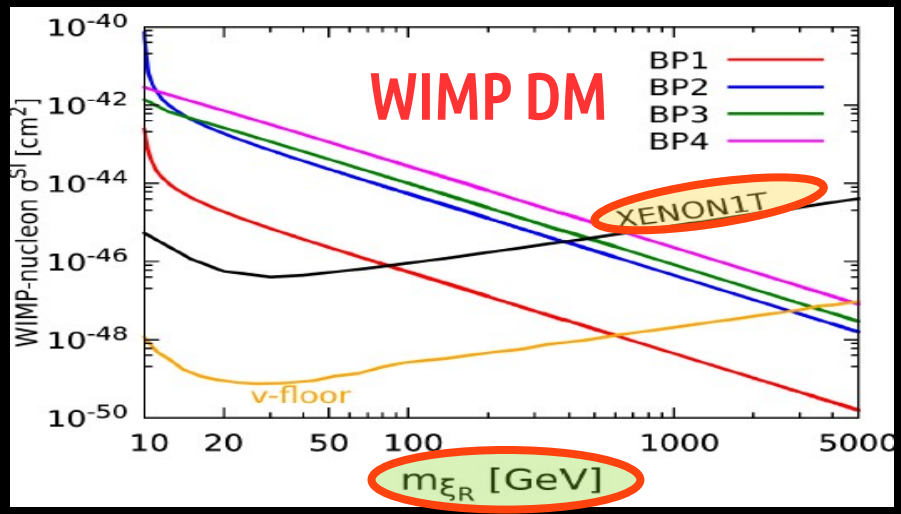
dark inverse typeI seesaw mechanism

LambdaCDM

Phys.Lett.B 821 (2021) 136609

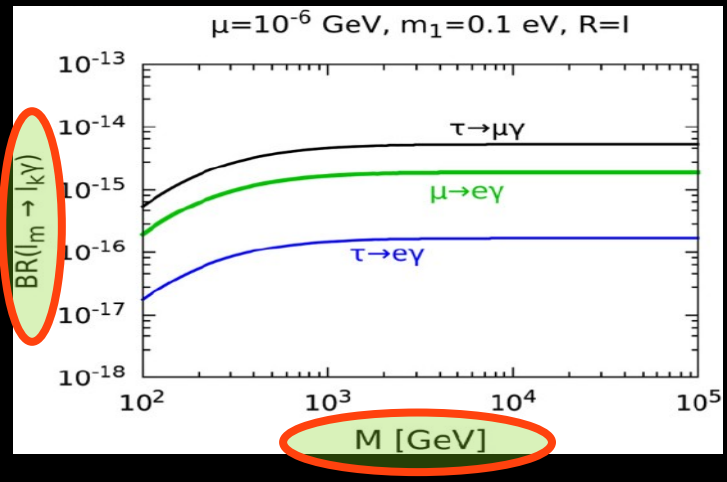


Xenon1T PhysRevLett.121.111302



e.g. large cLFV from inverse type I seesaw

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



neutrino properties from colliders

current oscillation data
can reconstruct type-II
so that it can be tested
at high-energies

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

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

Miranda et al PLB 829 (2022) 137110

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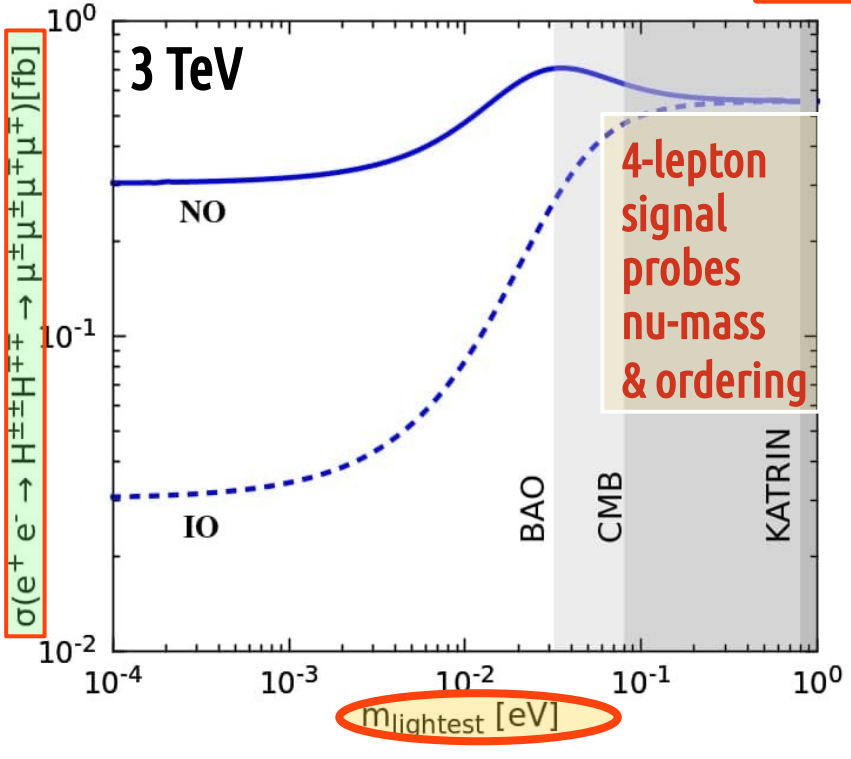

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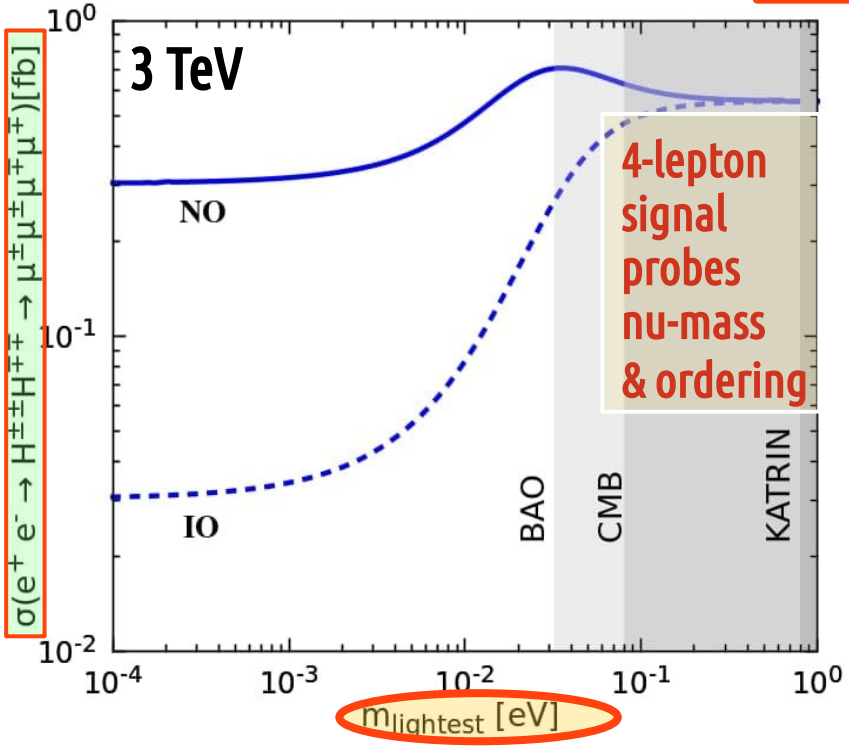
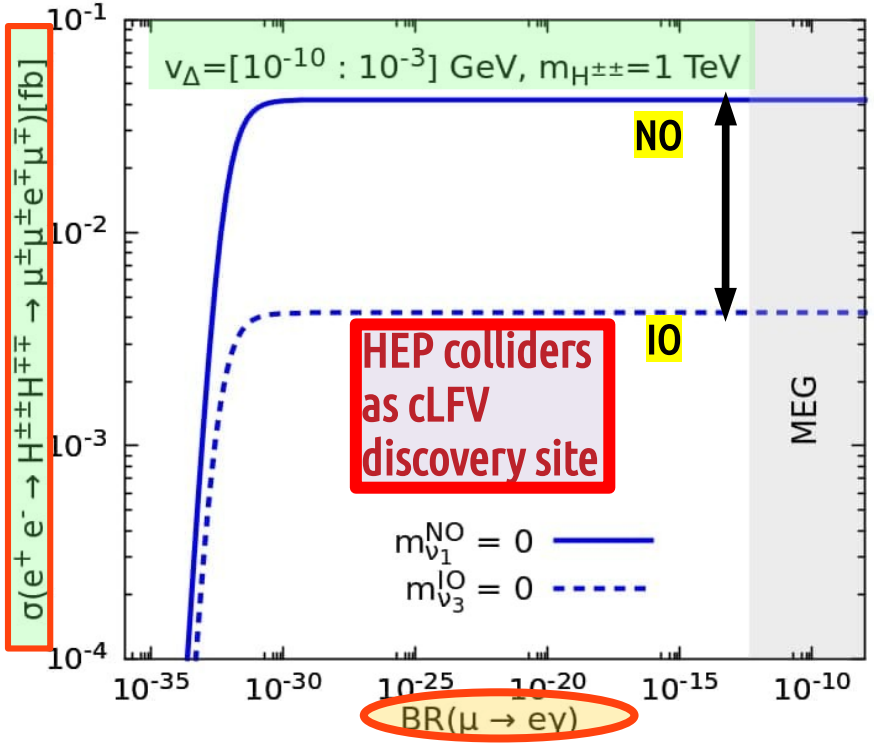
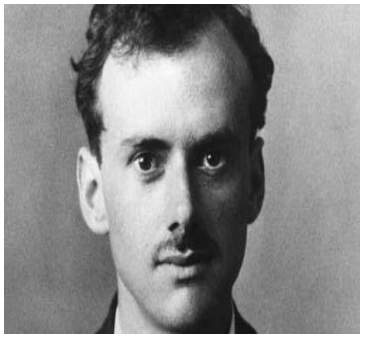
Miranda et al Phys.Rev.D105 (2022) 095020

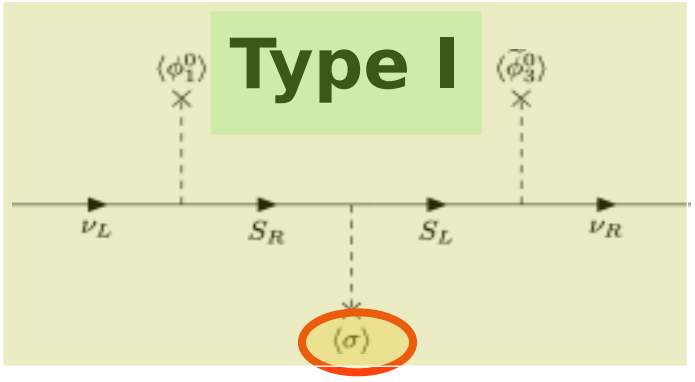


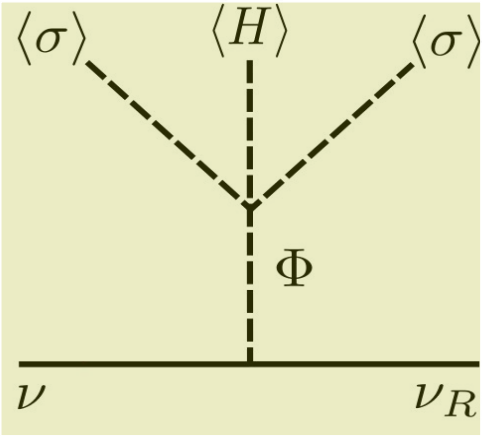
Miranda et al PLB 829 (2022) 137110



seesawing a la



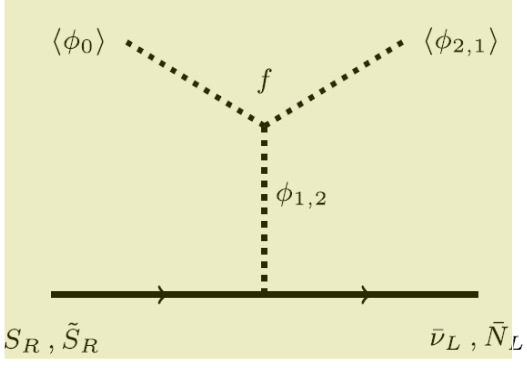




Type II

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

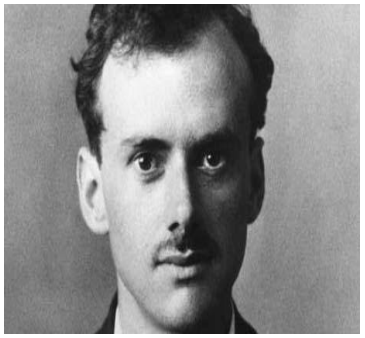
Phys.Rev. D98 (2018) 035009

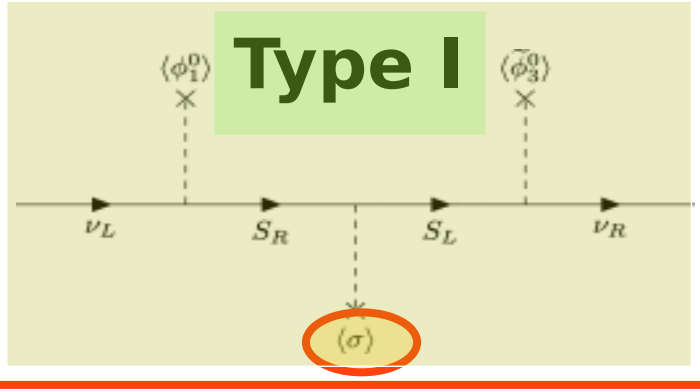
Phys.Lett. B781 (2018) 122-128

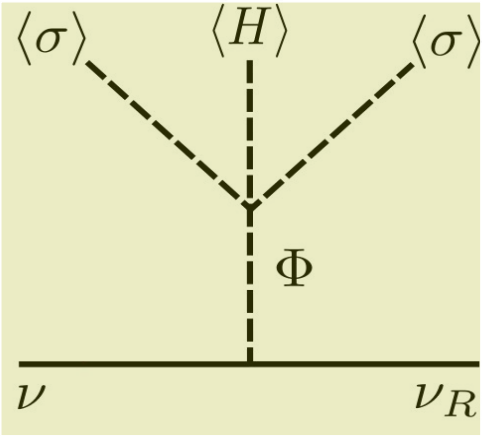
Addazi et al Phys.Lett. B759 (2016) 471-478

Phys.Lett. B755 (2016) 363-366

seesawing a la







Type II

symmetry protecting small neutrino mass

+ Diracness

Peccei-Quinn symmetry Phys.Lett.B 810 (2020) 135829

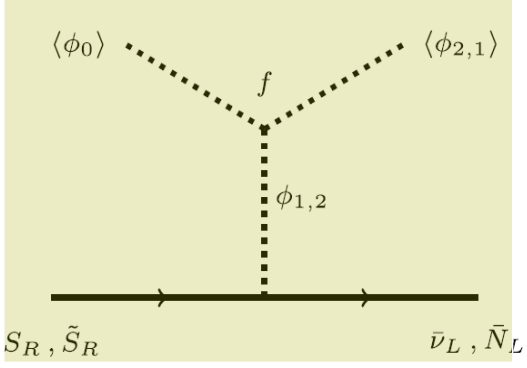
$$m_\nu^D \simeq \frac{y^{\nu_1}(y^S)^{-1}(y^{\nu_2})^T}{\sqrt{2}}\, v\, \frac{w}{v_\sigma}$$

SU3L

PQ

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



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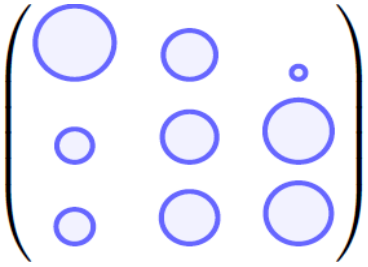
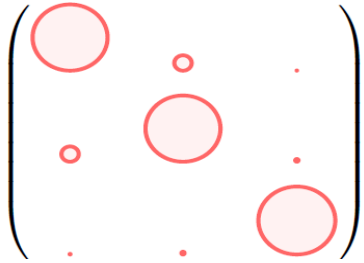
flavour legacy of oscillations

Q/L mixing pattern



versus



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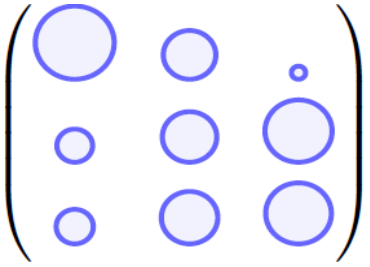
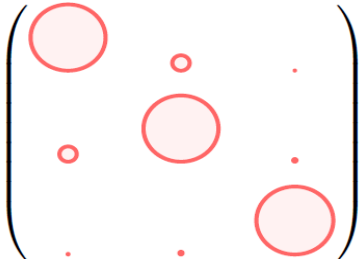
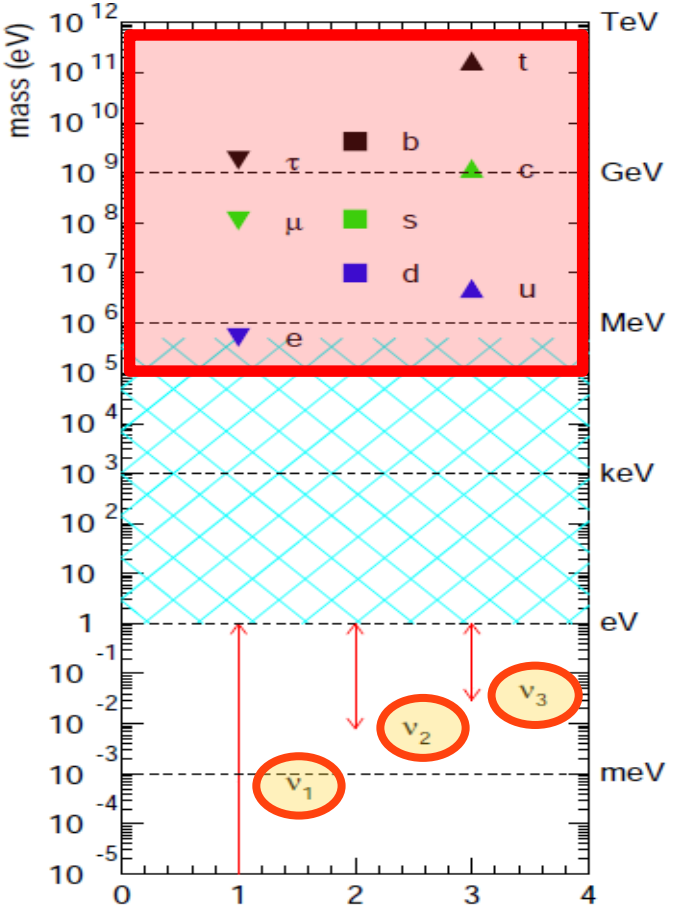


versus



Q/L mass hierarchies



flavour legacy of oscillations

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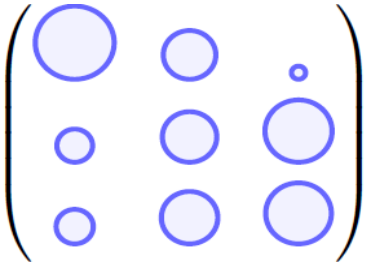

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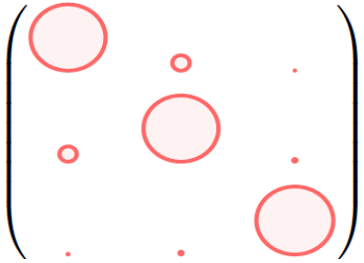
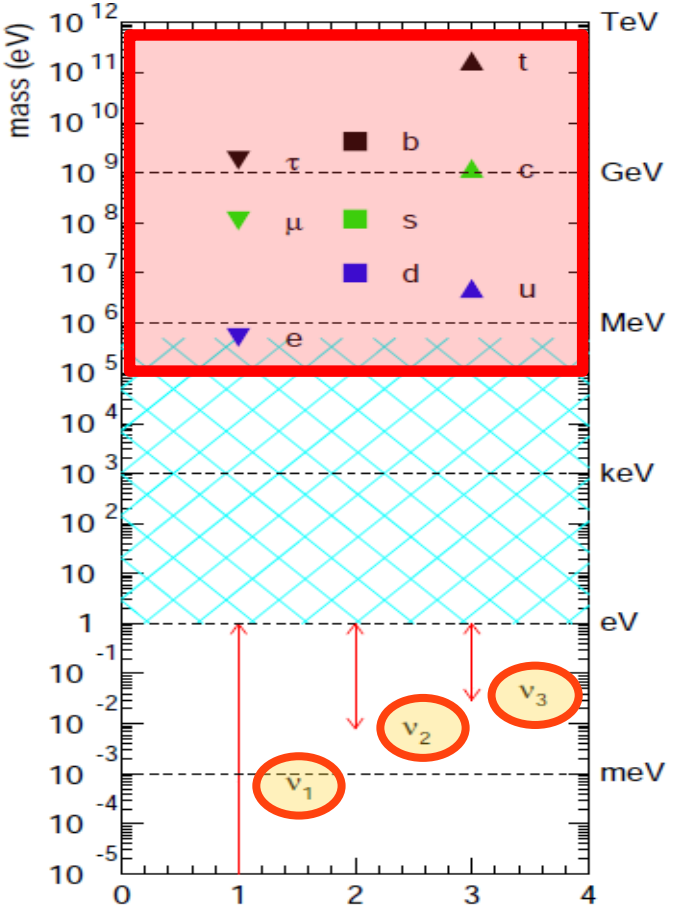


Q/L mass hierarchies

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

Golden Q-L mass relation

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



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**

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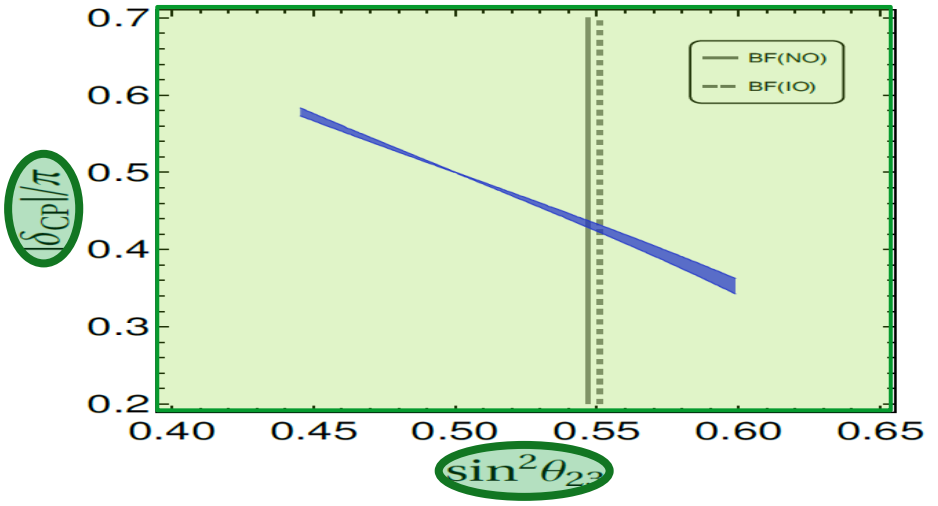
TM mixing pattern predicted from T'

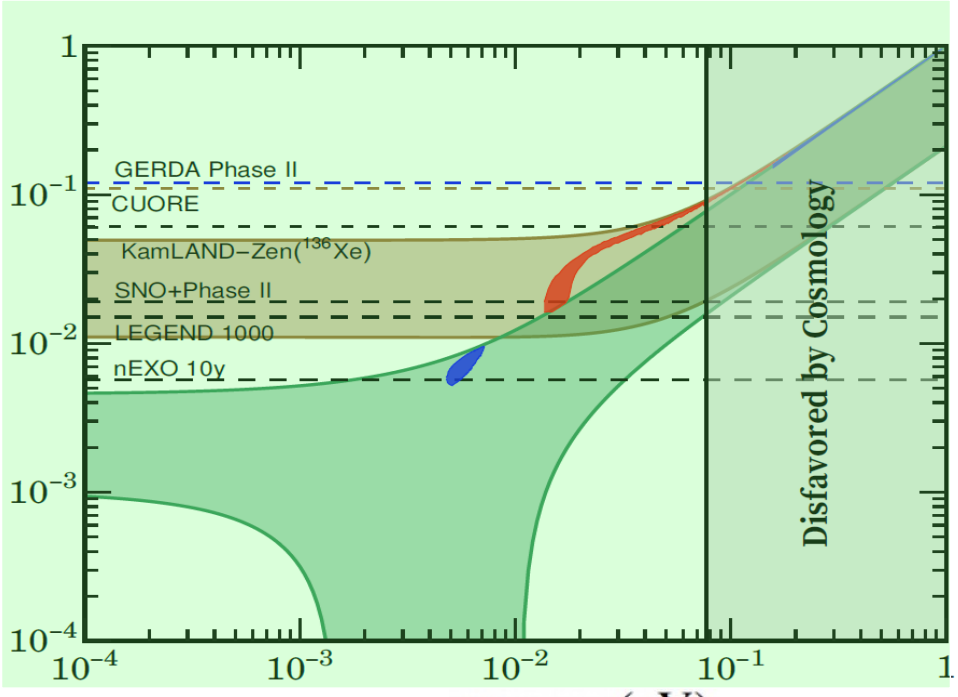
$$\cos^2\theta_{12}\cos^2\theta_{13} = \frac{2}{3}$$ **TM1 pattern**

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

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



TM1



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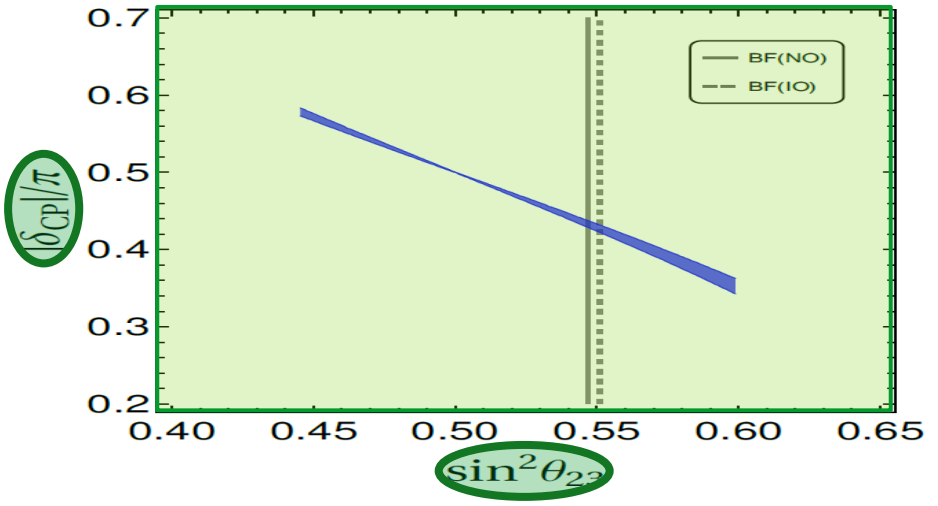
Chen et al Phys. Rev. D 102, 095014 (2020)

TM2

Another model with Dirac neutrinos
Chen et al JHEP01(2016)007
Phys. Rev. D95 (2017) 095030
Phys.Lett. B771 (2017) 524



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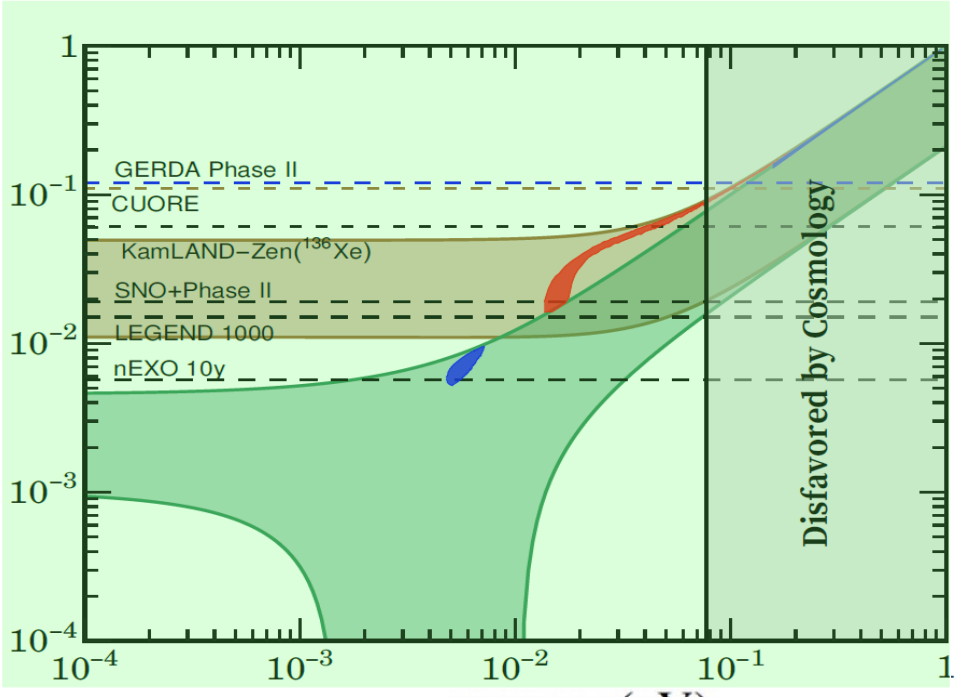
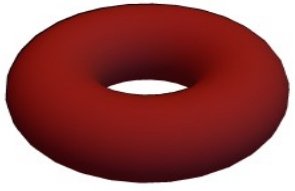


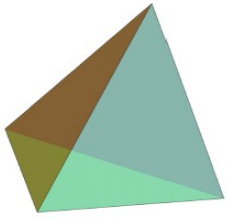
family symmetry from 6D orbifold

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

Phys.Lett.B 801 (2020) 135195
Phys.Rev.D 105 (2022) 055030



A4 family symmetry as emergent



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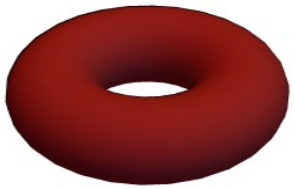

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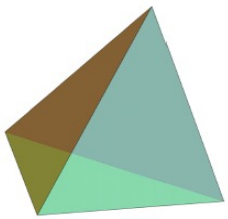

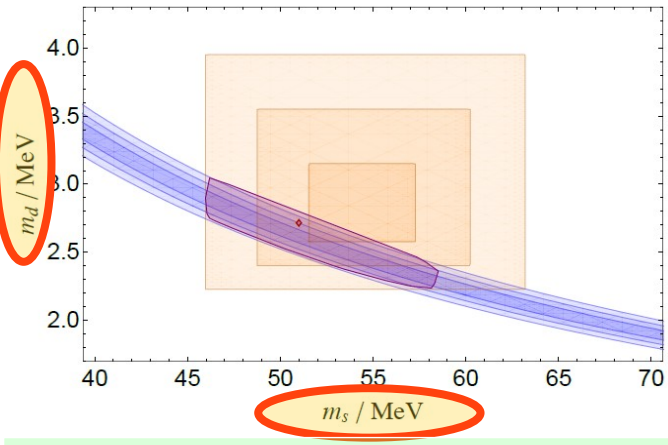

Good global fit of flavor observables

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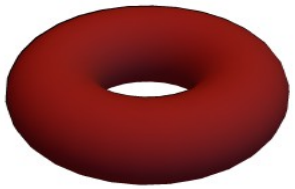
Phys.Lett.B 801 (2020) 135195
Phys.Rev.D 105 (2022) 055030



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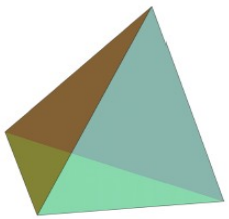
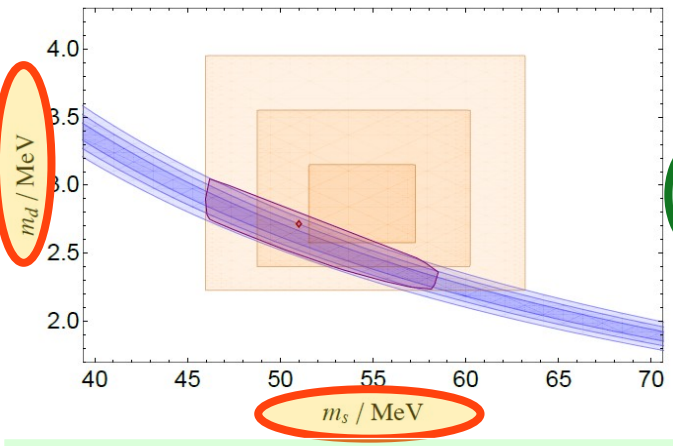
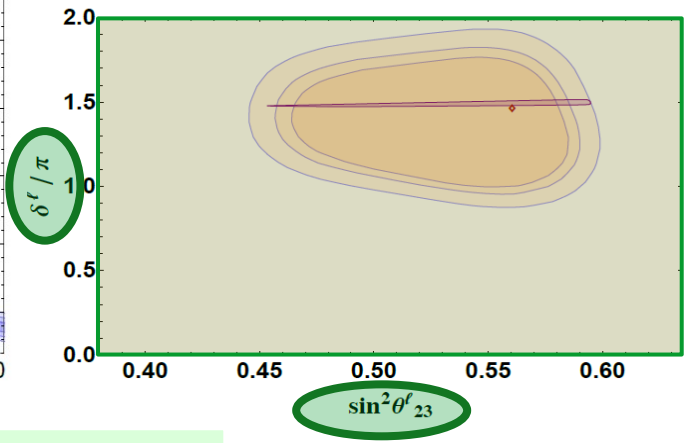
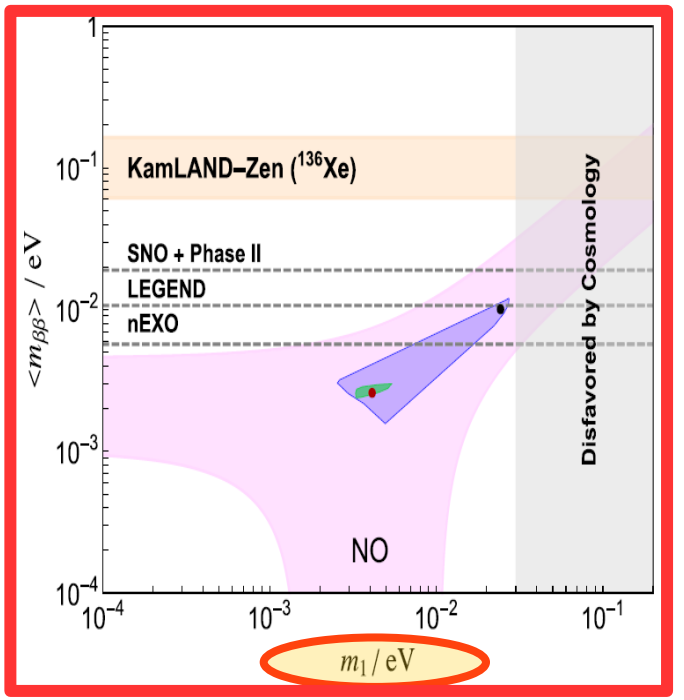


Sign of CP phase!

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

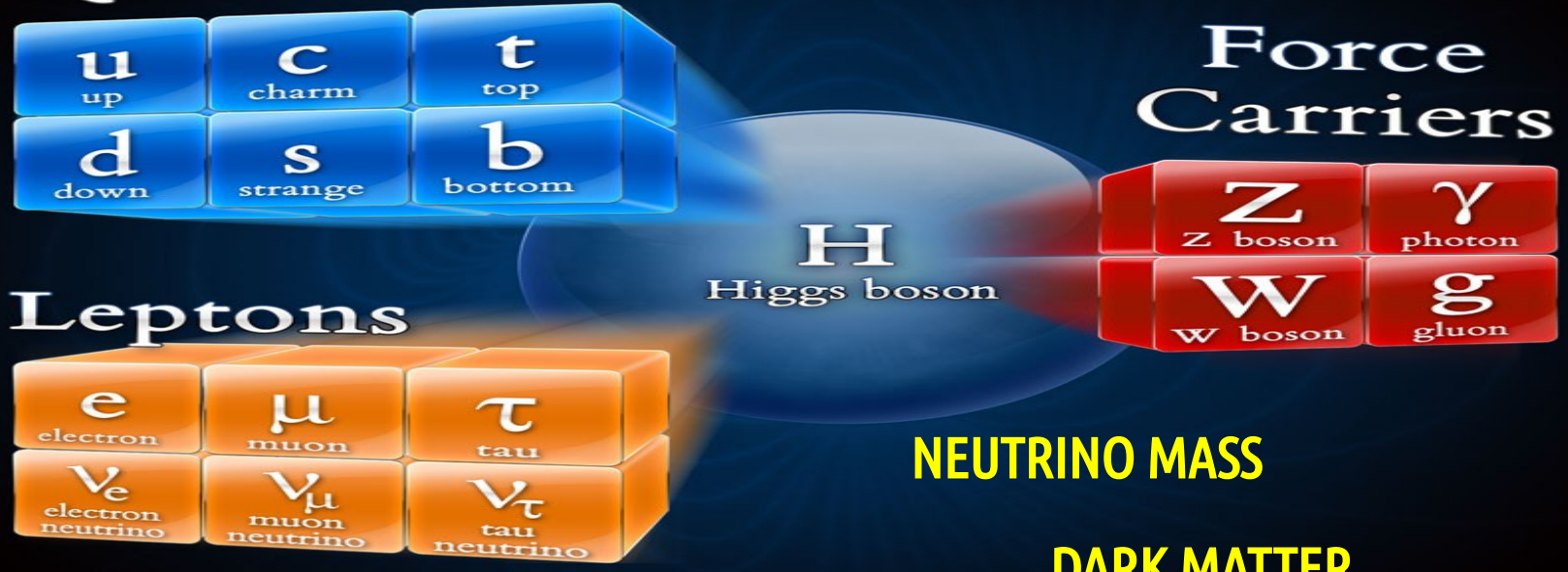






Good global fit of flavor observables

JHEP10(2020)190

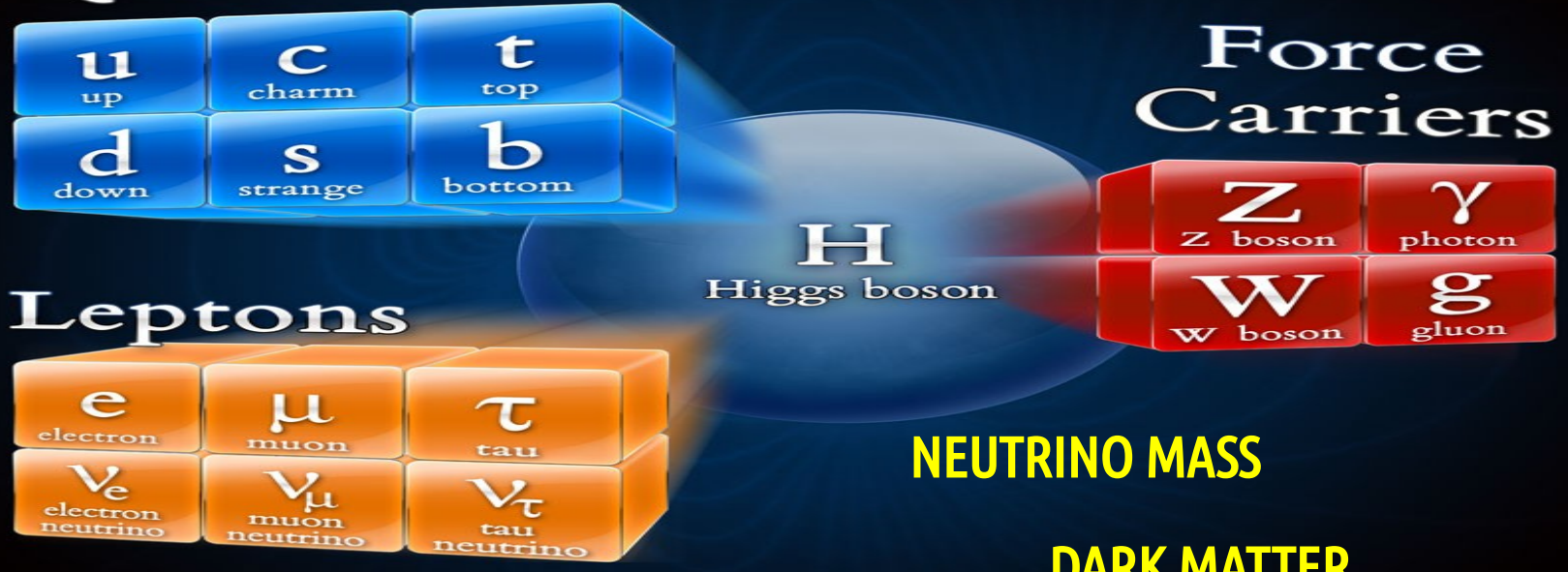


NEUTRINO MASS

DARK MATTER

NU-COMPLETION of SM

FLAVOR PROBLEM



NEUTRINO MASS

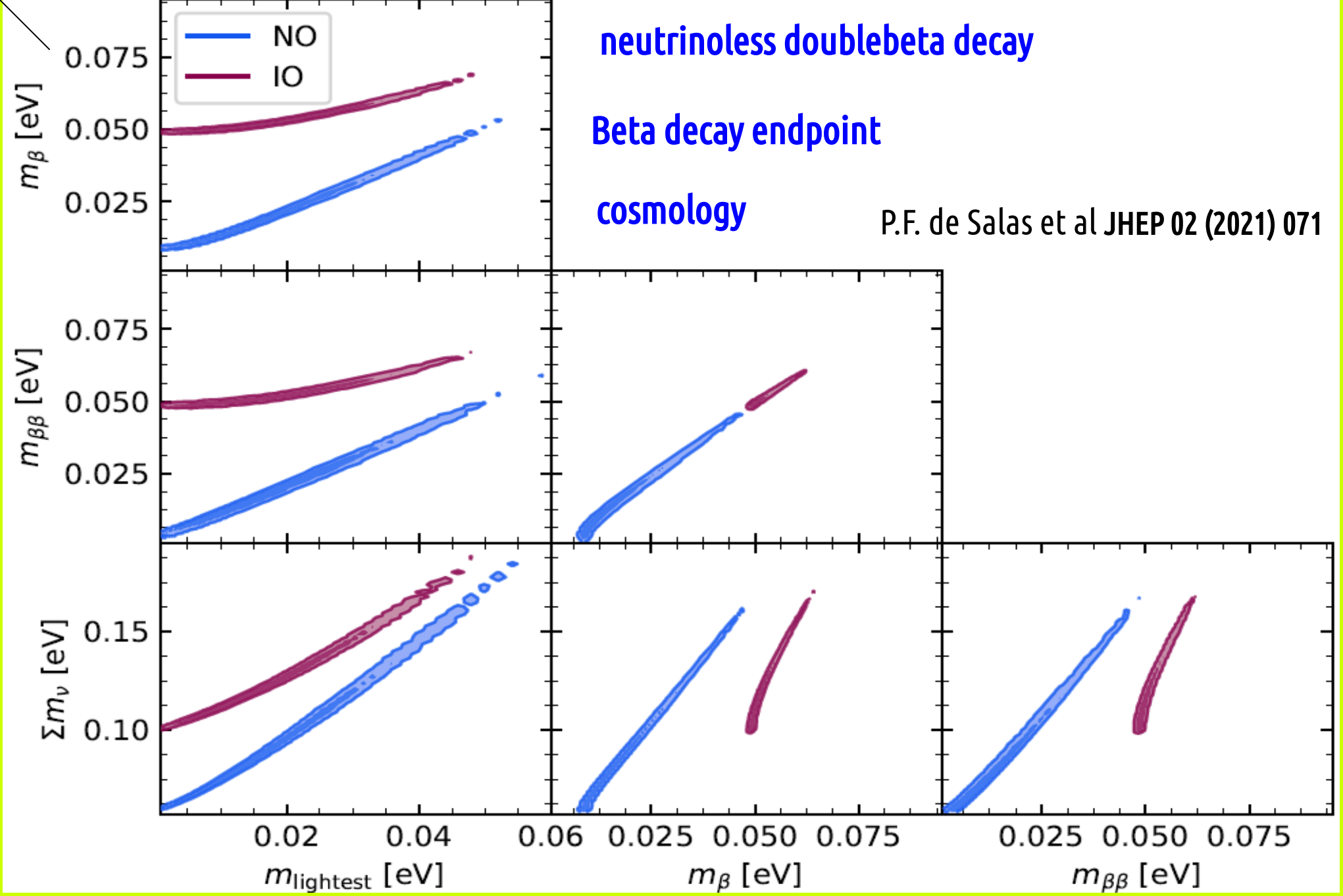
DARK MATTER

FLAVOR PROBLEM

NU-COMPLETION of SM

EW vacuum stability from seesaw
neutrinos & DM
scoto-seesaw
dark inverse seesaw
Diracness from **DM stability** …

Diracness from **PQ symmetry**
Warped flavordynamics
Family symmetry as **emergent**
cosmology from neutrinos
GWs from lepton # violation..



neutrinoless doublebeta decay

Beta decay endpoint

cosmology

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