neutrino oscillations and new physics oportunities

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Pascos, 2024, Qui-Nhon, Vietnam

ASTROPARTICLES
Astroparticles and High Energy Physics Group

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GOBIERNO DE ESPAÑA
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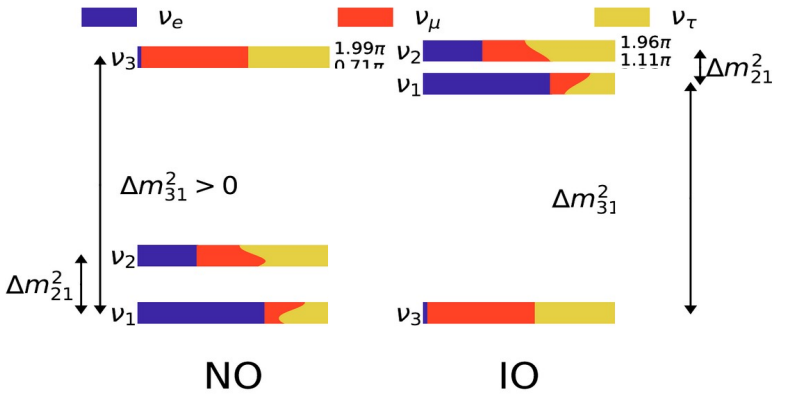
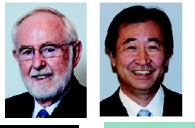
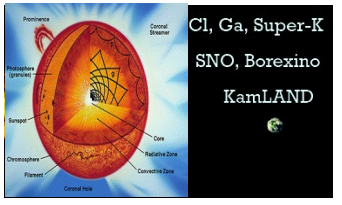
GENERALITAT VALENCIANA
Conselleria de Educación, Universidades y Empleo

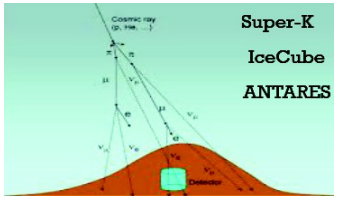
current status

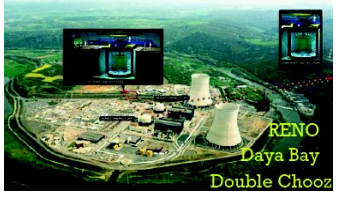
Mass ordering problem

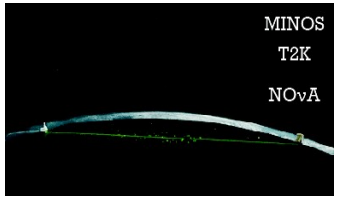




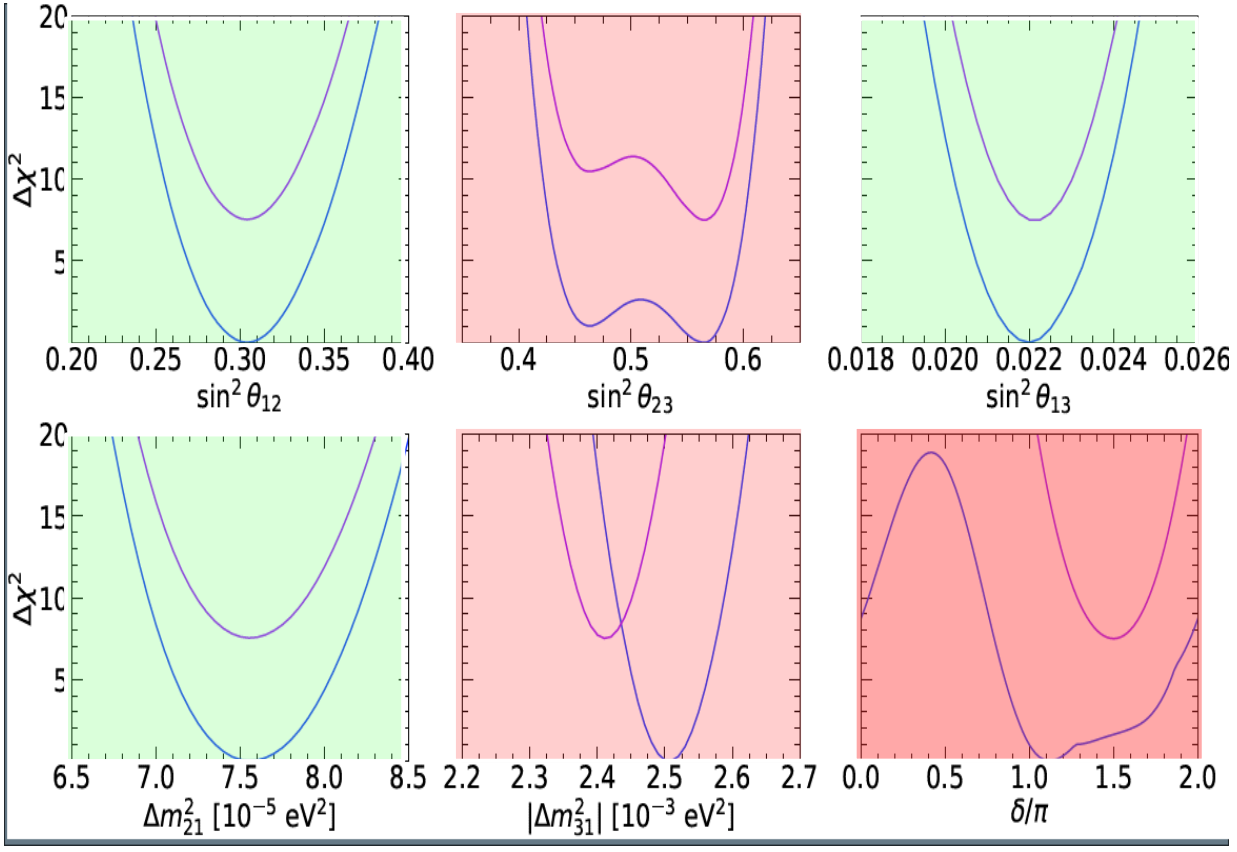








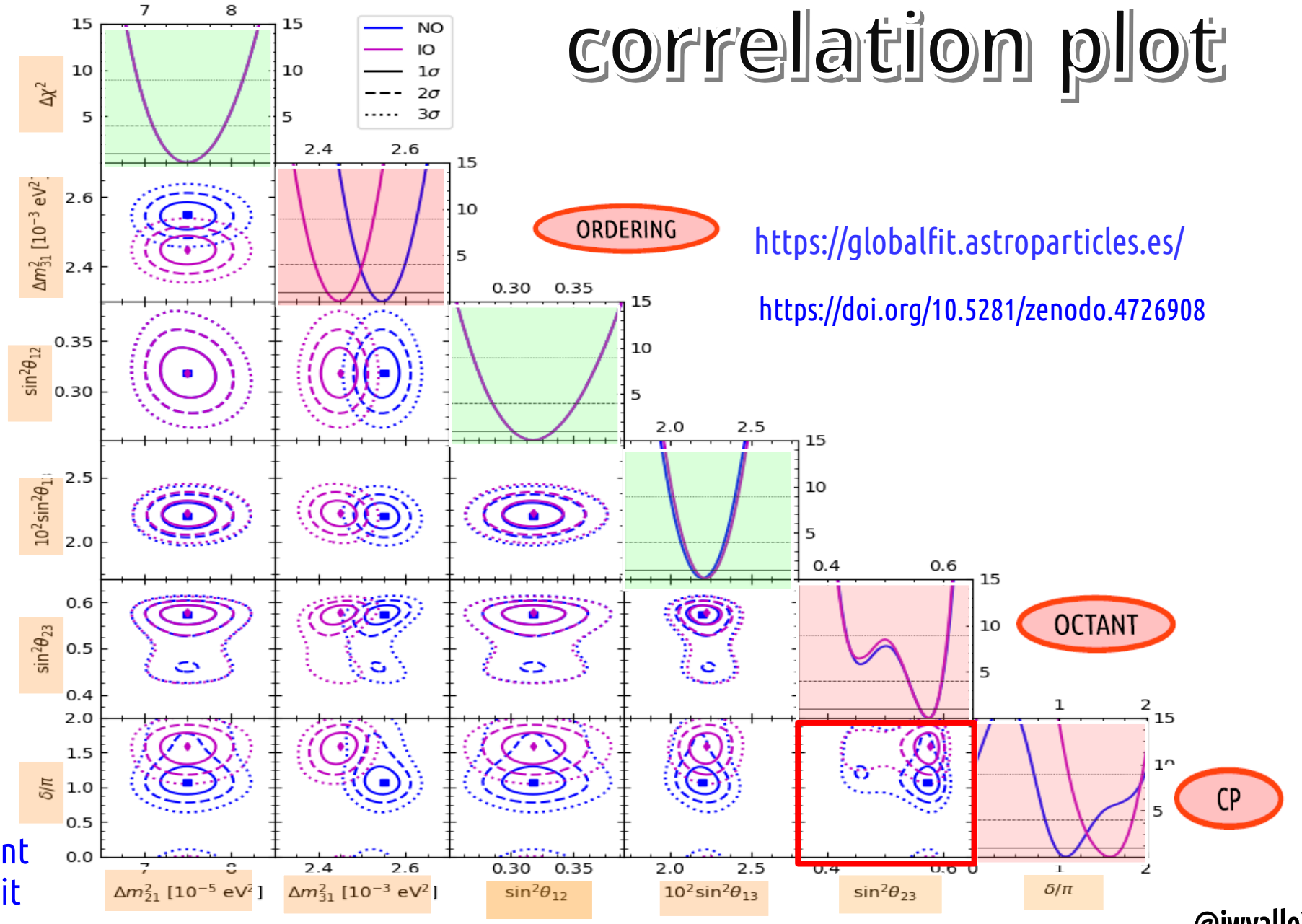
PF de Salas et al JHEP02(2021)071



Courtesy of Mariam Tórtola, post Nu2024 results

@jwvalle2

correlation plot



ORDERING

OCTANT

CP

https://globalfit.astroparticles.es/

https://doi.org/10.5281/zenodo.4726908

PF de Salas et al JHEP02(2021)071

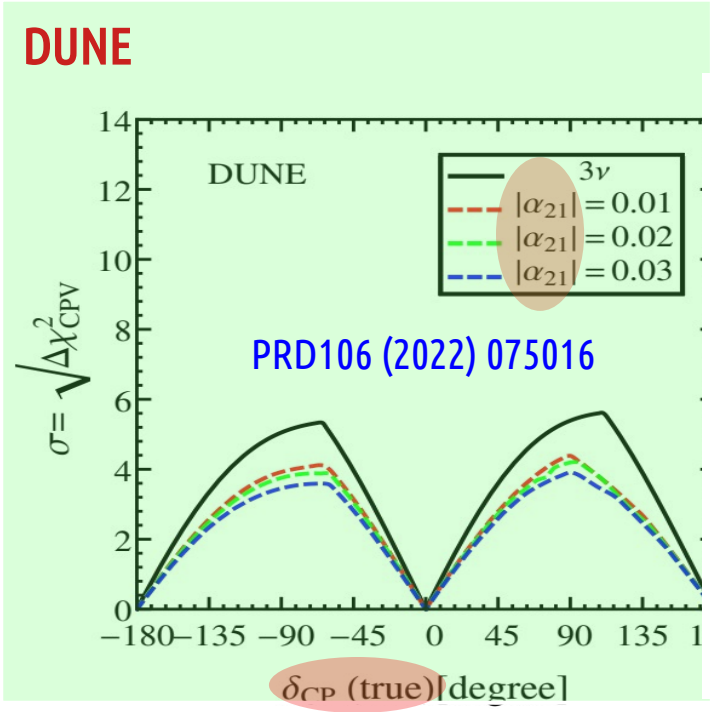
Agreement with NuFit and Bari

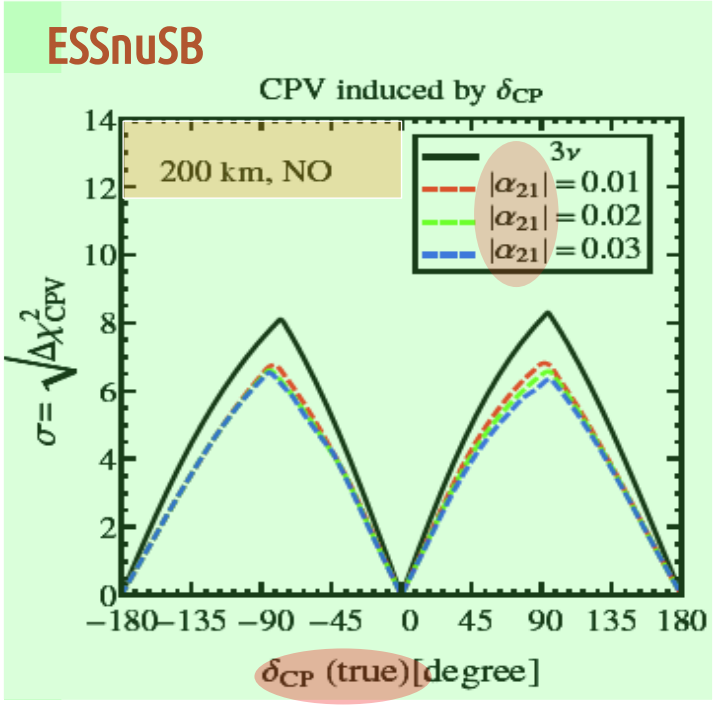
@jwvalle3

CPV

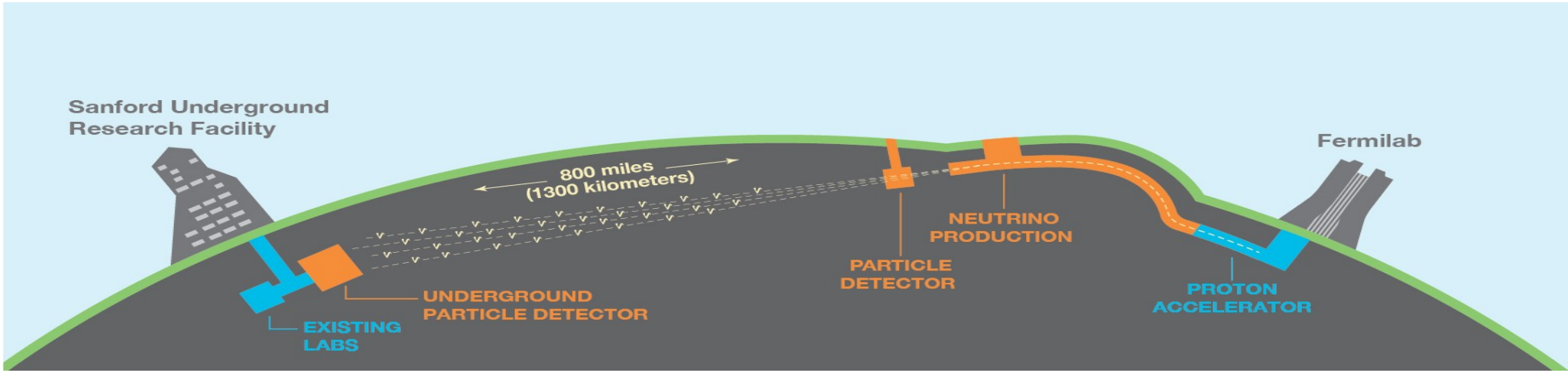
PhysRevLett117(2016)061804
New J.Phys. 19 (2017) 9, 093005
PhysRevD97 (2018) 095026

DUNE 2008.12769
Hyper-K
ESSnuSB





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



For a CP review Prog.Part.Nucl.Phys. 60 (2008) 338

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Improvements expected from **JUNO**

especially in combination with long-baseline neutrino beams

NovA and **T2K or DUNE and Hyper-K**

Cabrera et al 2008.11280

Synergy with neutrino telescopes

KM3NET/ORCA

S. Aiello et al JHEP03(2022)055

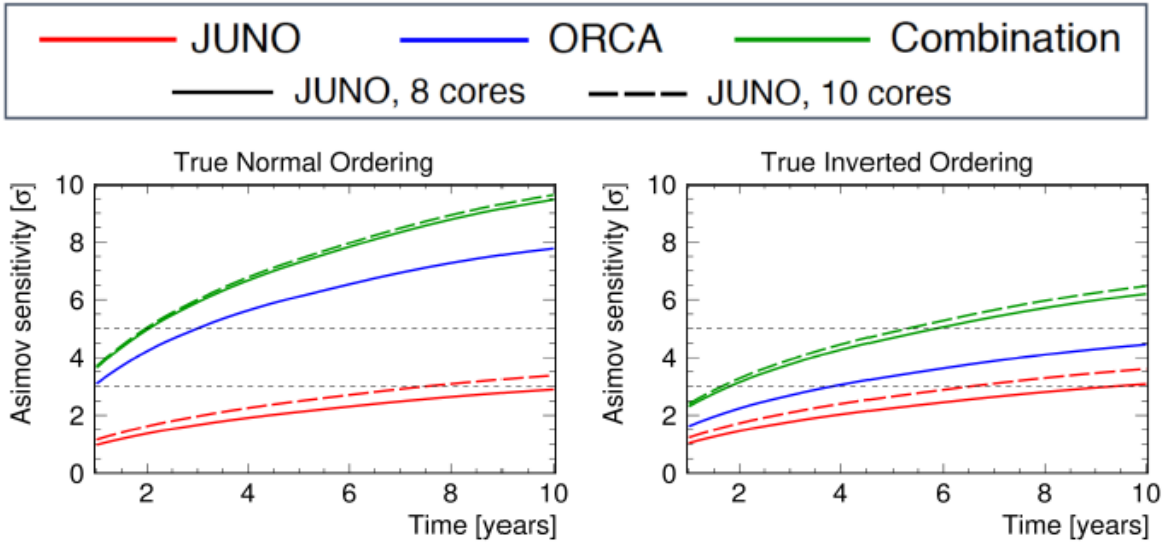
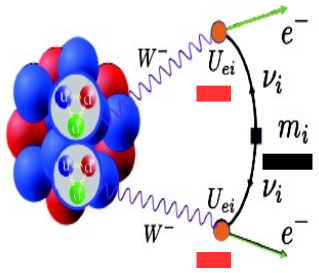


Figure 7. NMO sensitivity as a function of time for only JUNO (red), only ORCA (blue), and the combination of JUNO and ORCA (green), considering 2 (solid) or 4 (dashed) Taishan NPP reactors, corresponding respectively to 8 or 10 reactor cores at 53 km from JUNO.

neutrinoless doublebeta decay

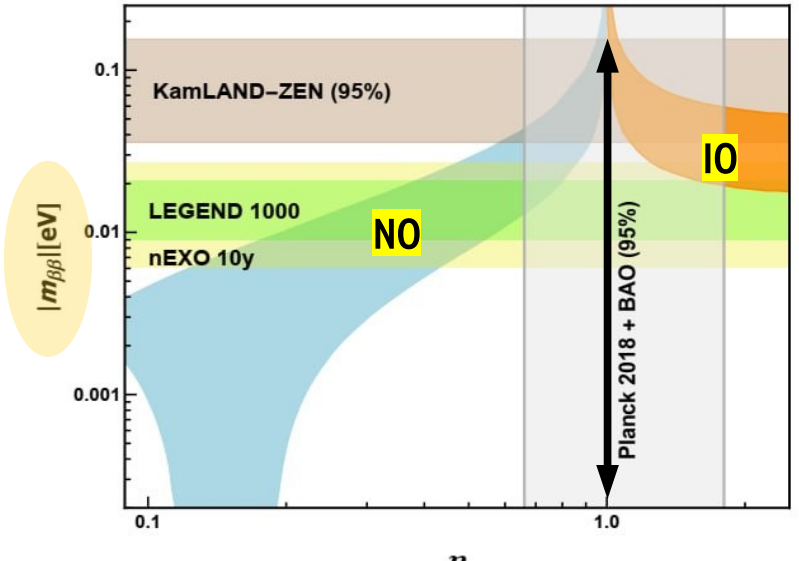
$$\left|\sum_j U_{ej}^2 m_j\right| = \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{2i\phi_{12}} + s_{13}^2 m_3 e^{2i\phi_{13}}\right|$$



Original symmetrical parametrization
Schechter & JV PRD22 (1980) 2227
Rodejohann, JV Phys.Rev. D84 (2011) 073011
Versus PDG phase convention

KamLAND-Zen 2203.02139 GERDA 2009.06079

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

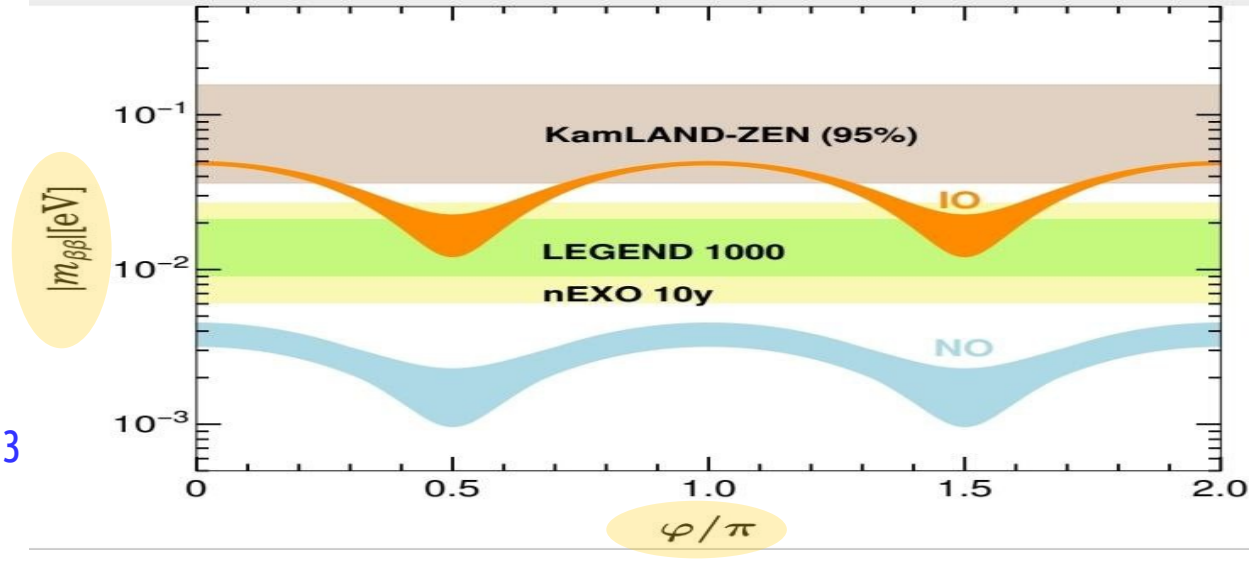


Lattanzi et al JHEP 10 (2020) 213

Nearly degenerate

- ## 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

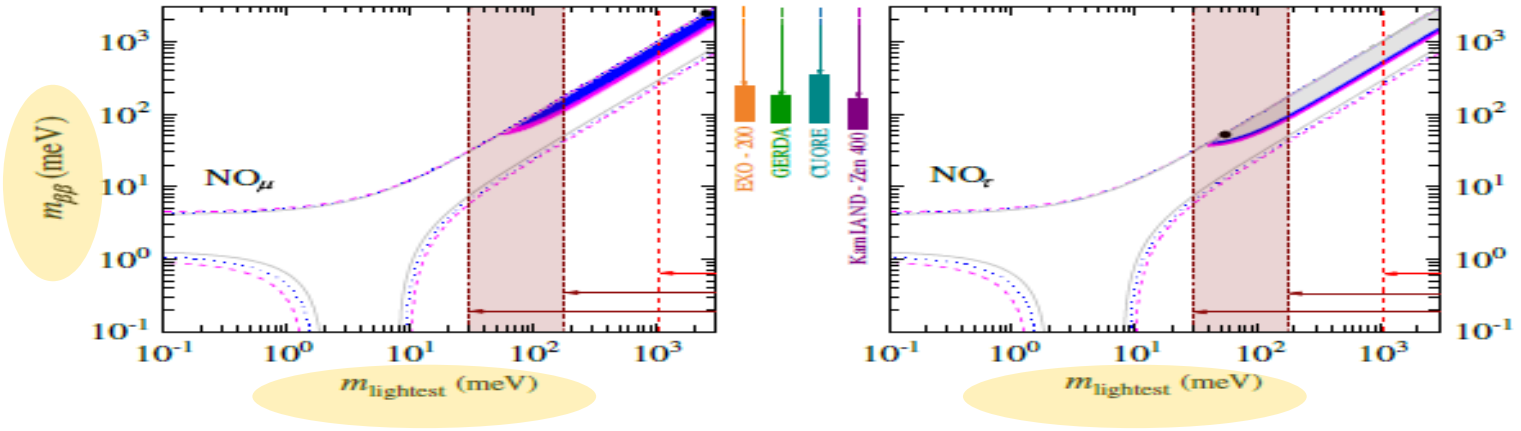
@jwvalle6

3-massive case

Lower bounds from oscil. legacy + family symmetries

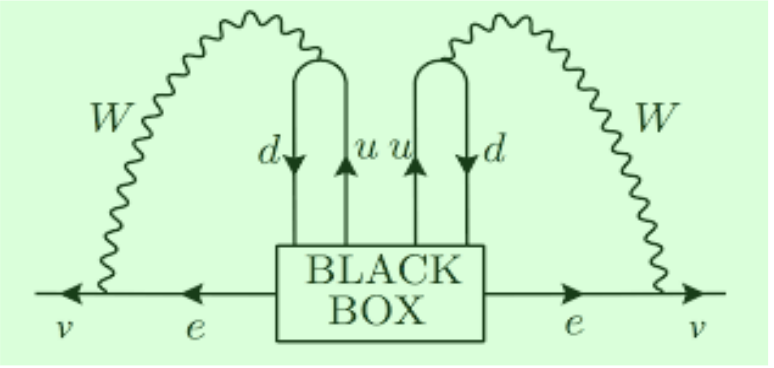
Dorame et al PhysRevD86(2012)056001
Dorame et al Nucl.Phys.B861 (2012) 259-270
King et al Phys.Lett. B724 (2013) 68-72 etc

From Barreiros et al JHEP04(2021)249



Significance

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

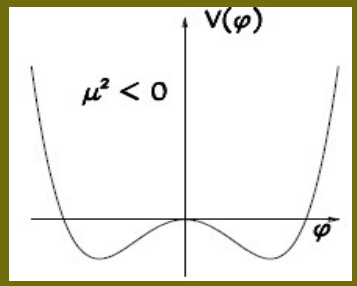


Origin of neutrino mass

stability

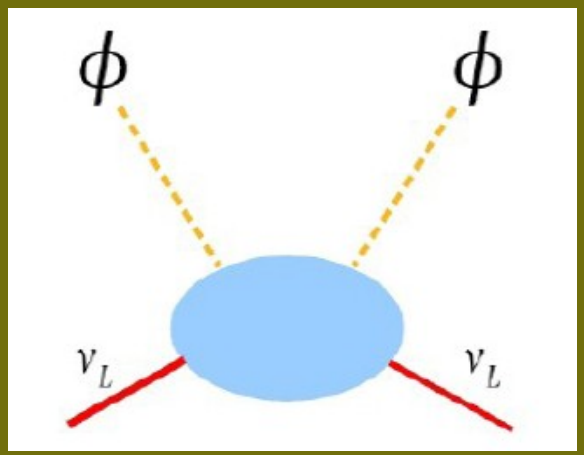
SEESAW dynamics

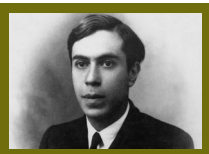
$$v_3 v_1 \sim v_2^{\,2}$$

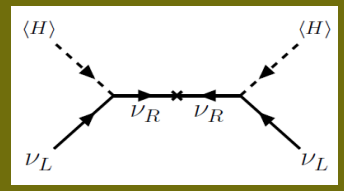


Mandal et al PRD101 (2020) 115030

JHEP03(2021)212 & JHEP07(2021) 029

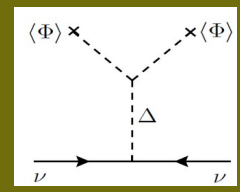






TYPE I

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



TYPE II

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

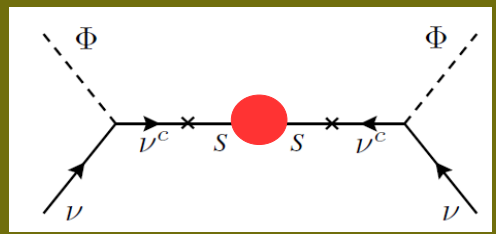
L-R seesaw # of Rs = # Ls (3,3)

SM seesaw any # of singlets (3,m)

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

$m_{\beta\beta}$

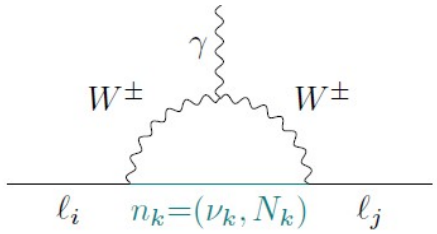
- **LOW-SCALE Type1 SEESAW (3,6) ISS & LSS**



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

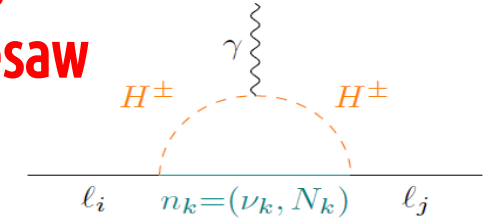
@jwvalle8

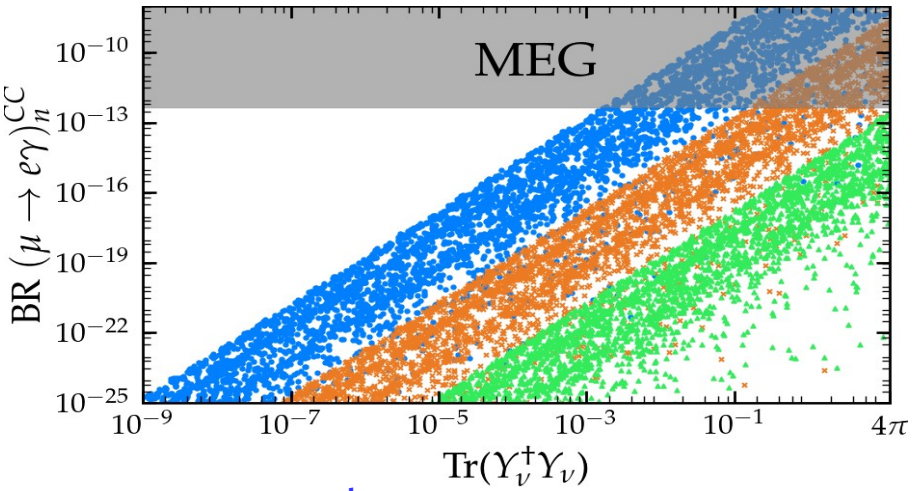
CC Lepton Flavor Violation In low-scale seesaw

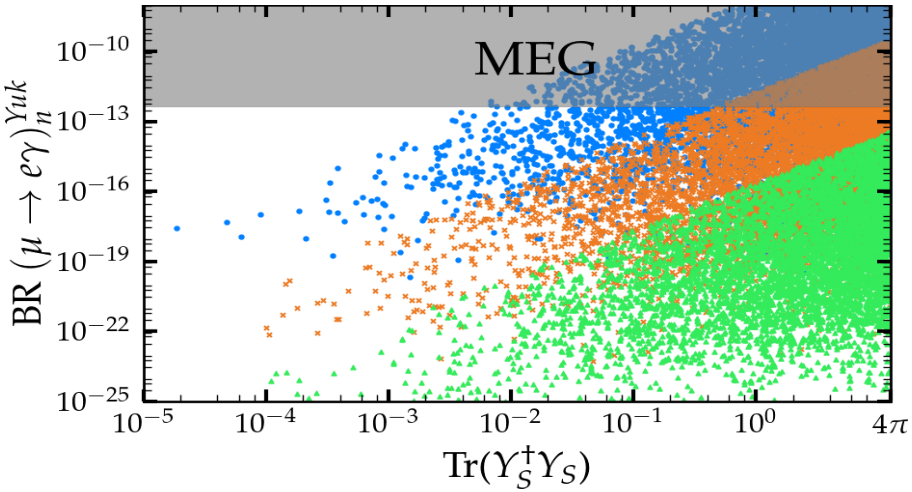


(3,6)

Leptophilic Higs cLFV in linear seesaw







From Batra et al 2305.00994

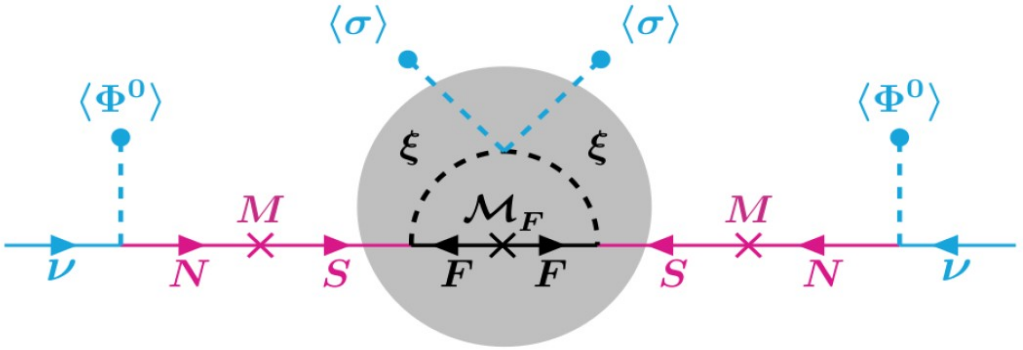
$M_N = 1\ TeV$ $M_N = 10\ TeV$ $M_N = 100\ TeV$

cLFV persists in the massless neutrino limit

Bernabeu et al B187 (1987) 303-308


DARK MATTER
PROTON
PHOTON
e'
NEUTRINO
MUON
NEUTRON
QUARK
VISIBLE MATTER
e
e
DARK ELECTRONS
NEUTRALINO
AXION
AXION
GRAVITINO
Wimp
DARK NEUTRON

dark inverse seesaw



Dark loop+seesaw/symmetry protection

is dark matter the radiative seed of neutrino mass?

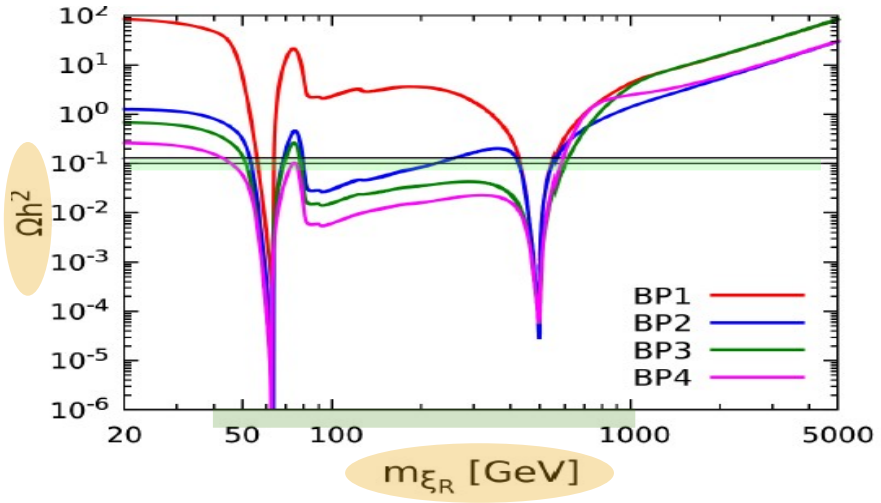
Mandal et al
Phys.Lett.B821 (2021) 136609

low-scale type-1

dark inverse seesaw

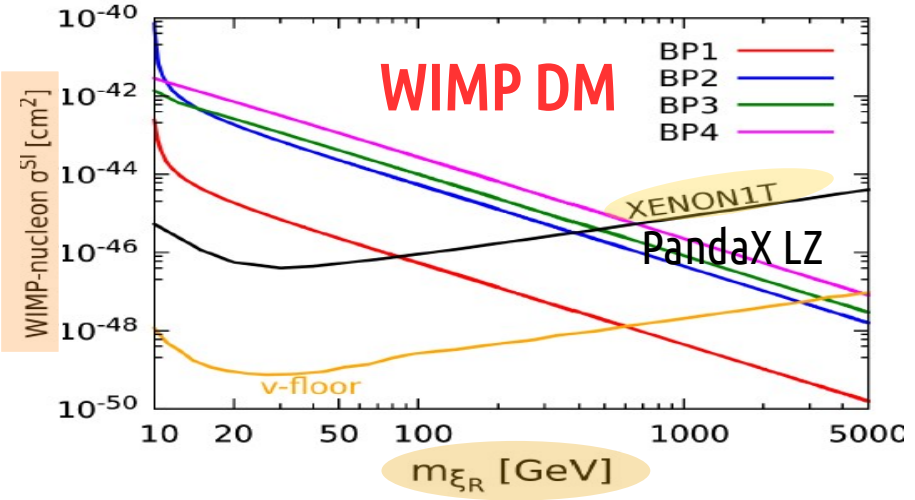
LambdaCDM

Phys.Lett.B821 (2021) 136609



Xenon1T PhysRevLett.121.111302

PandaX Lux-Zepellin

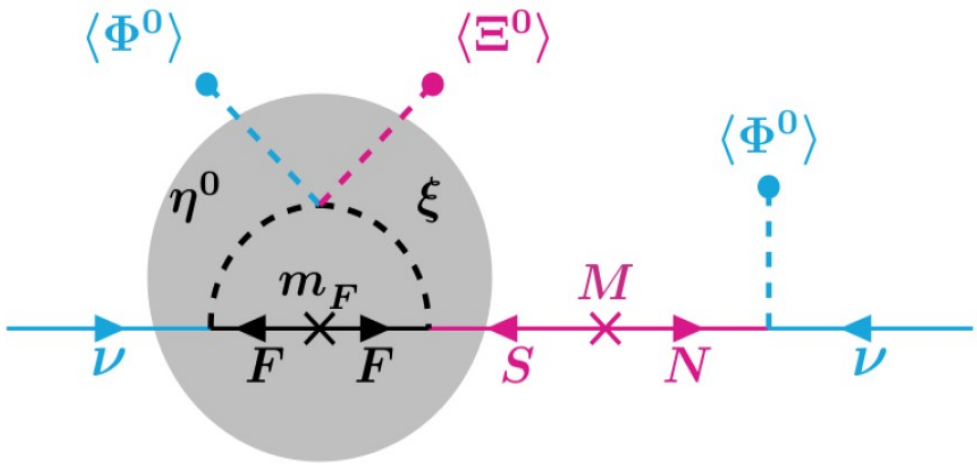


+ charged lepton flavor violation

@jwvalle12

low-scale type-1 **dark linear seesaw** (3,6)

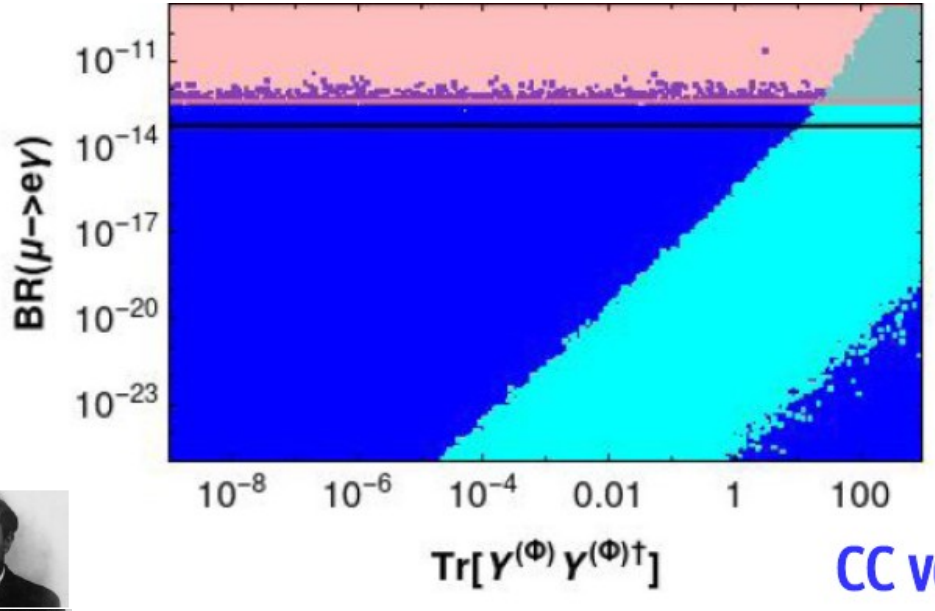
$$M_\nu = \begin{pmatrix} 0_{3\times3} & m_D & \varepsilon \\ m_D^T & 0_{3\times3} & M \\ \varepsilon^T & M & 0_{3\times3} \end{pmatrix}$$

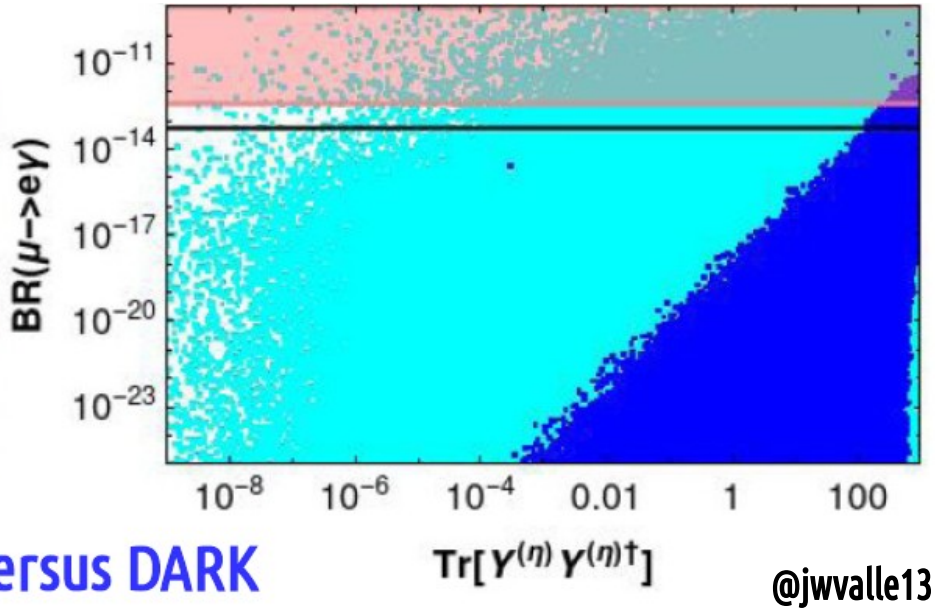


Carcamo, Vishnudath, J.V. JHEP 09 (2023) 046

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

(Also Batra, Camara, Joaquim, 2305.01687)





CC versus DARK

@jwvalle13

scotoseesaw

Solar scale from SCOTOGENIC

Atm scale from SEESAW

Ma hep-ph/0601225
Tao hep-ph/9603309
Dark-mediated nu-mass loop

Simplest scoto-seesaw
Phys.Lett.B 789 (2019) 132-136
Phys.Lett.B 819 (2021) 136458

LOOP
TREE

$$\frac{\Delta m^2_{\rm SOL}}{\Delta m^2_{\rm ATM}} = 0.0302^{+0.0012}_{-0.0010}$$

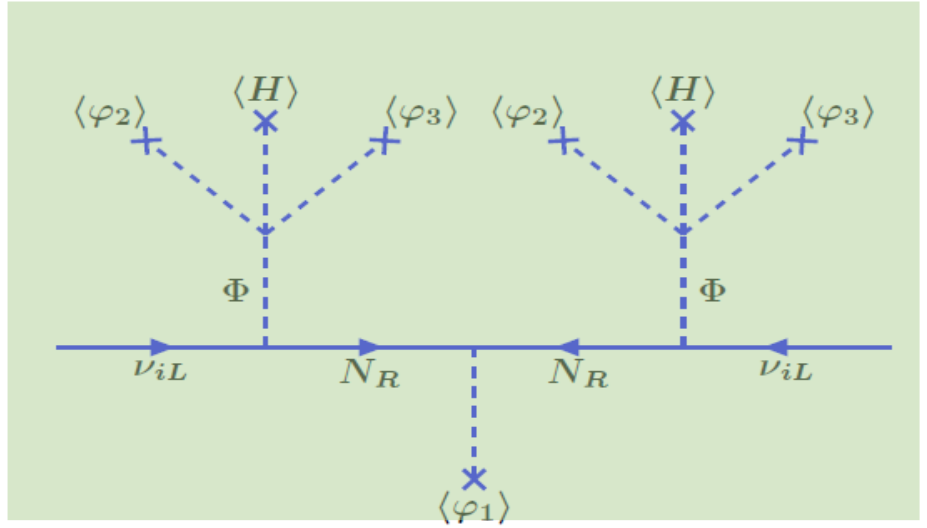
@jwvalle14

atm scale from seesaw

Leite, Sadhukhan, Valle
Phys.Rev.D 109 (2024) 3, 035023

Tiny induced leptophilic higgs vev
Allows for a lower seesaw scale

(3,3)



dynamical scoto-seesaw

Drell-Yan pair production

Simplest scoto-seesaw
Phys.Lett.B 789 (2019) 132-136
Phys.Lett.B 819 (2021) 136458

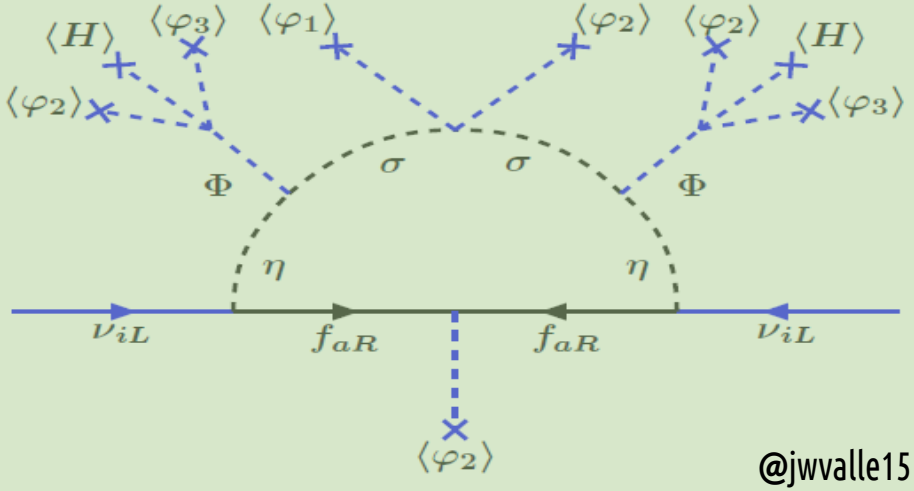
LOOP

TREE

$$\frac{\Delta m^2_{\rm SOL}}{\Delta m^2_{\rm ATM}} = 0.0302^{+0.0012}_{-0.0010}$$

solar scale from scoto

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



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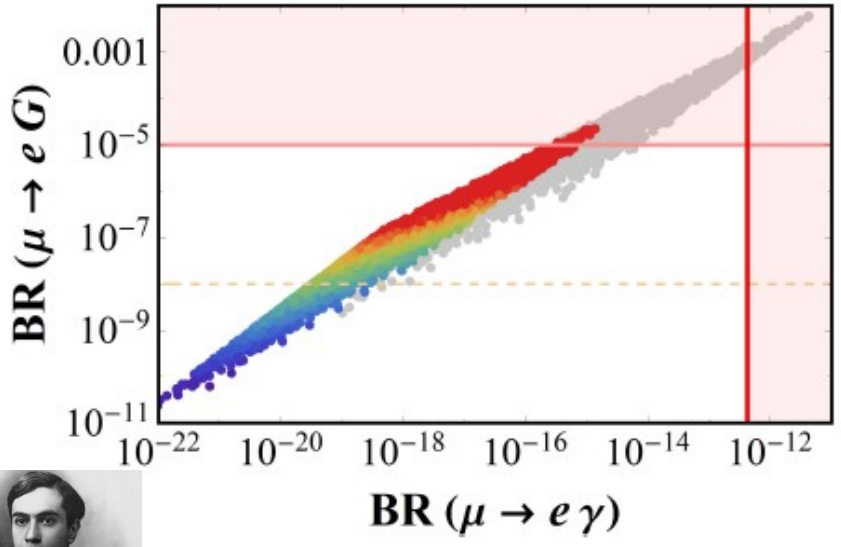
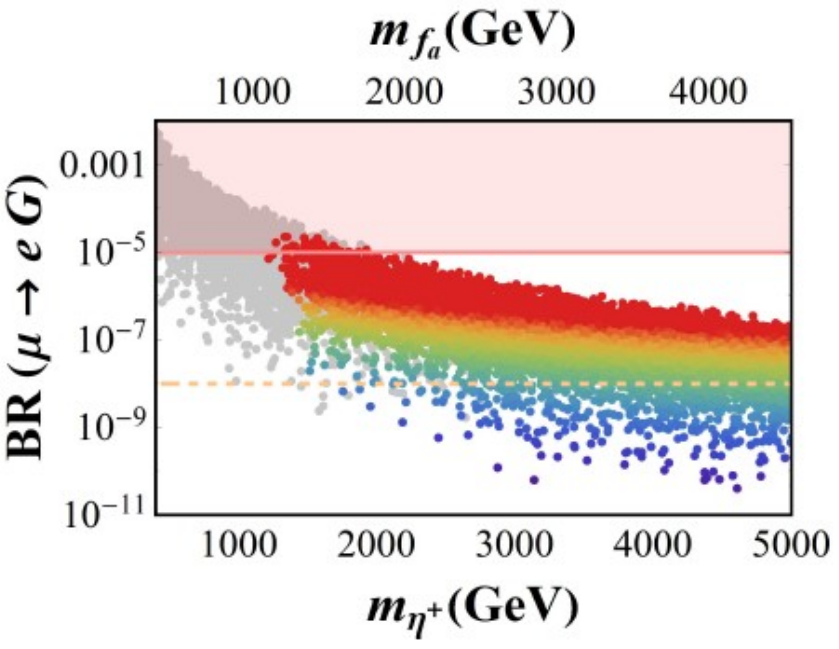
+ charged lepton flavor violation

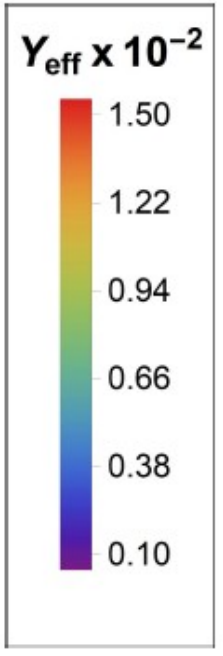
Goldstone boson

Leite, Sadhukhan, Valle
Phys.Rev.D 109 (2024) 3, 035023

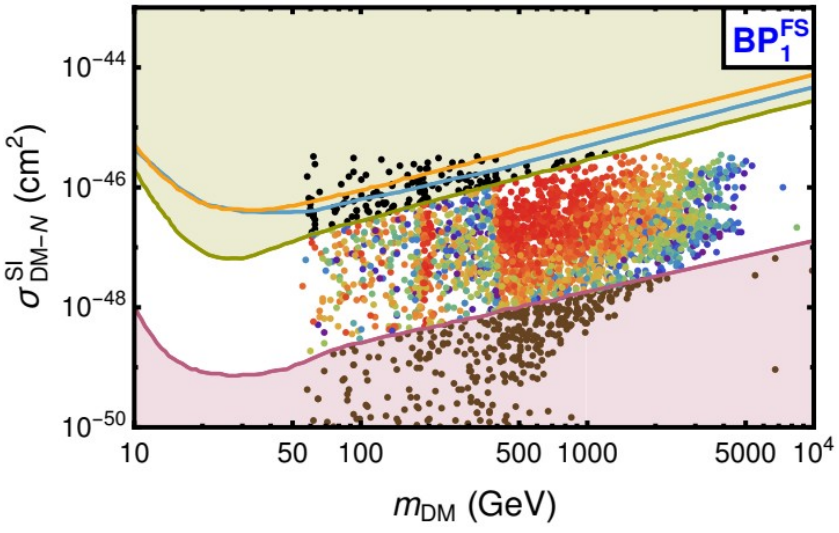
$$G \simeq \frac{1}{\sqrt{14}}\left(5\frac{v_\Phi^2}{v_H v_\varphi}A_H - 5\frac{v_\Phi}{v_\varphi}A_\Phi + A_{\varphi_1} - 2A_{\varphi_2} + 3A_{\varphi_3}\right)$$



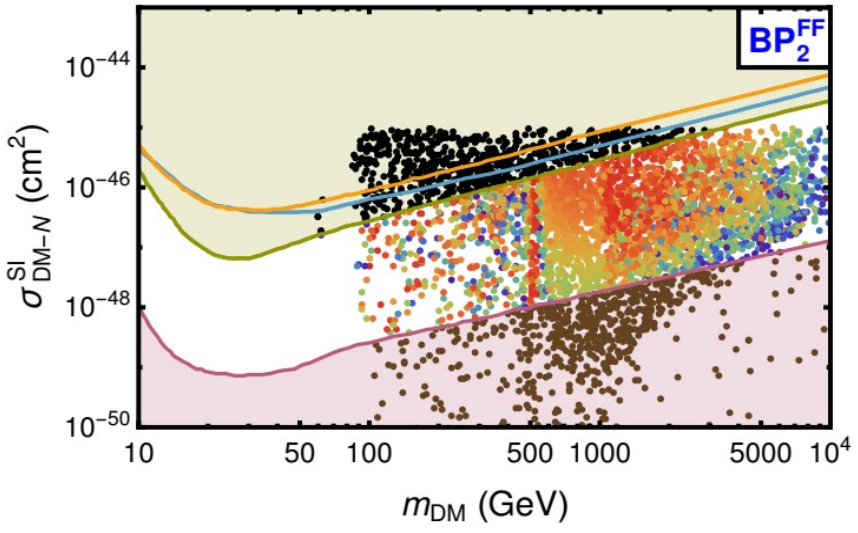




@jwvalle16

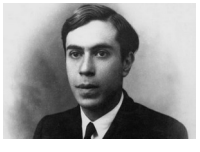


Higher v_Ω (4 GeV): Fermion-Scalar Coannihilation



Lower v_Ω (1.5 GeV): Fermion-Fermion Coannihilation

LFV Process	Current Bound	Future Sensitivity
$\mathcal{B}(\mu \to e\gamma)$	4.2×10^{-13} [44]	6.0×10^{-14} [45]
$\mathcal{B}(\mu \to 3e)$	1.0×10^{-12} [46]	$\sim 10^{-16}$ [47, 48]
$\mathcal{C}(\mu, Au \to e, Au)$	7.0×10^{-13} [49]	–
$\mathcal{C}(\mu, Ti \to e, Ti)$	4.3×10^{-12} [49]	$\sim 10^{-18}$ [50]
$\mathcal{C}(\mu, Pb \to e, Pb)$	4.6×10^{-11} [49]	–
$\mathcal{C}(\mu, Al \to e, Al)$	–	$\sim 10^{-17}$ [51, 52]



$\xi_i = (\Omega h_i^2 / \Omega h^2)$

0.2 0.4 0.6 0.8 1.0

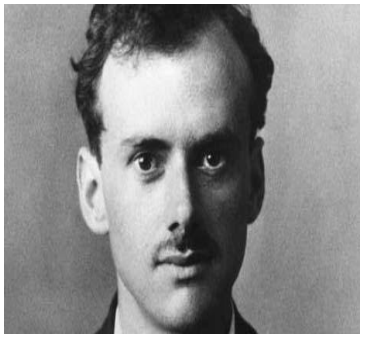
KSV 2308.09135

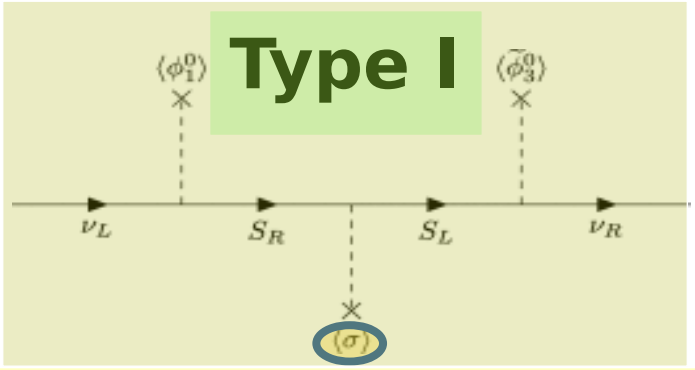
DBD lower bound

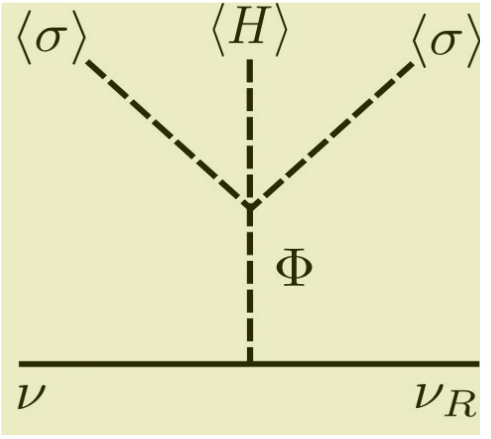
colliders

@jwvalle18

seesawing a la







Type II

symmetry protecting small neutrino mass

+ Diracness

Peccei-Quinn symmetry

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

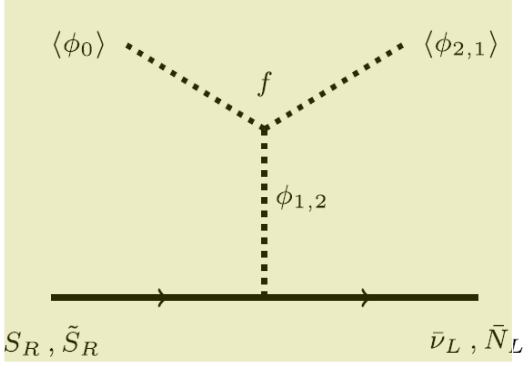
w ← SU3L

v_σ ← PQ

Phys.Lett.B 810 (2020) 135829

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

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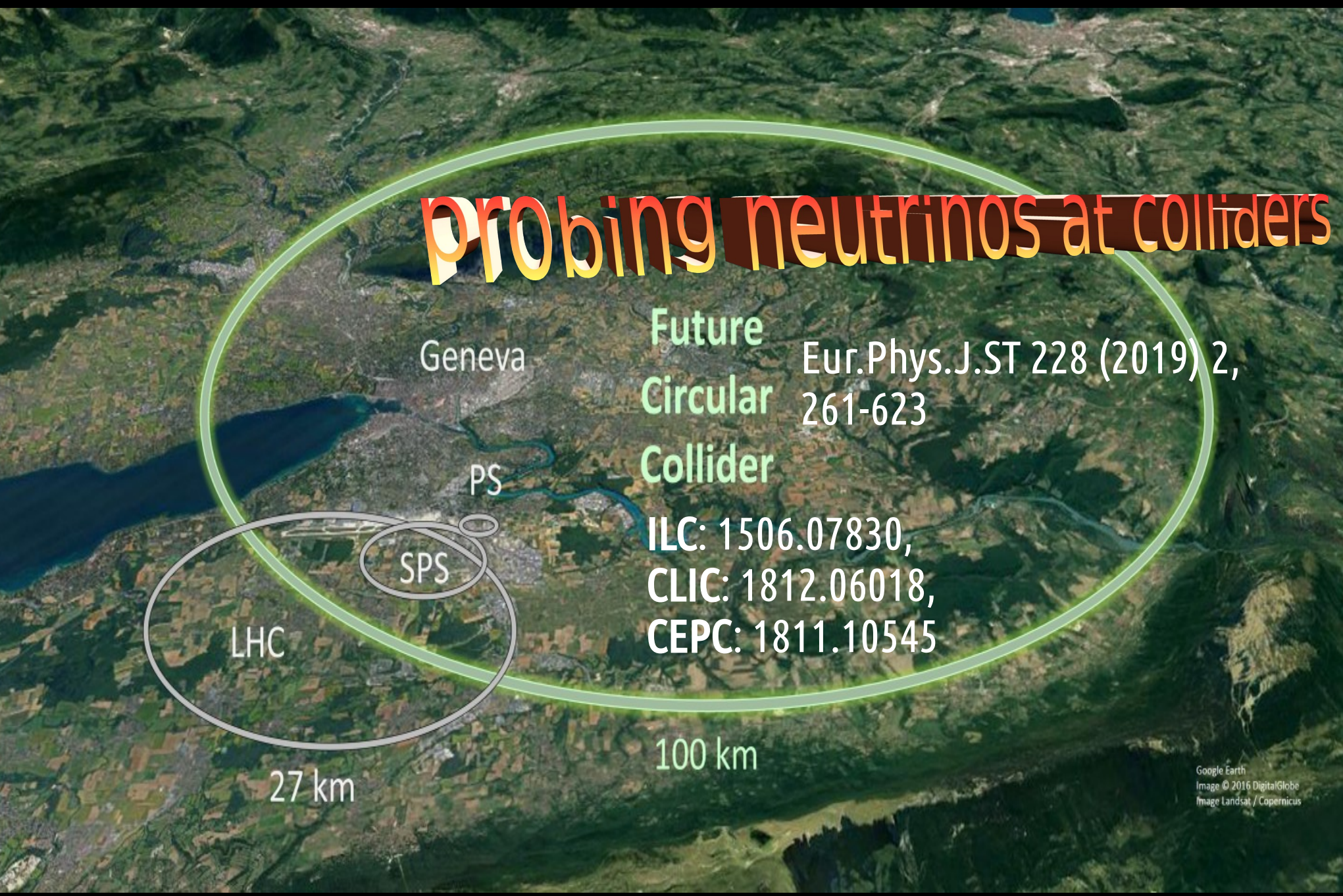
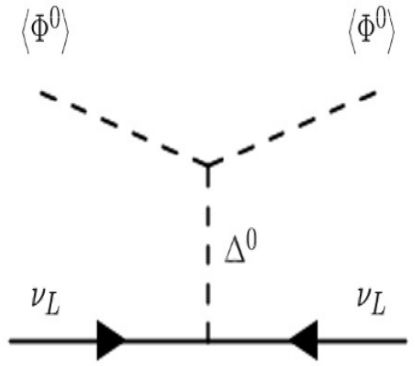

Probing neutrinos at colliders
Future
Circular
Collider
Geneva
PS
SPS
LHC
27 km
100 km
Eur.Phys.J.ST 228 (2019) 2, 261-623
ILC: 1506.07830,
CLIC: 1812.06018,
CEPC: 1811.10545
Google Earth
Image © 2016 DigitalGlobe
Image Landsat / Copernicus

low-scale type-2

triplet seesaw

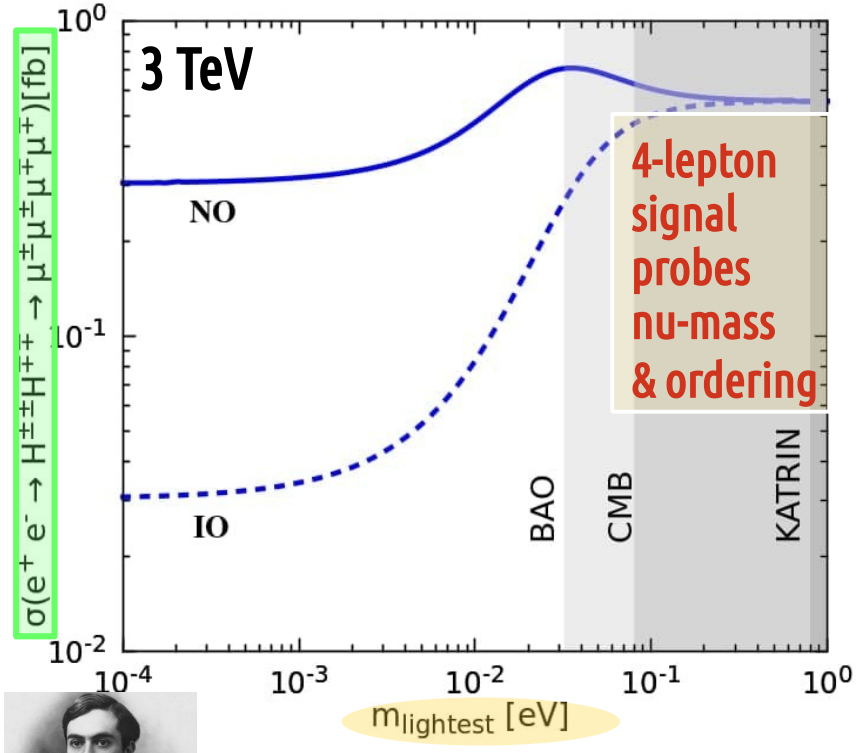


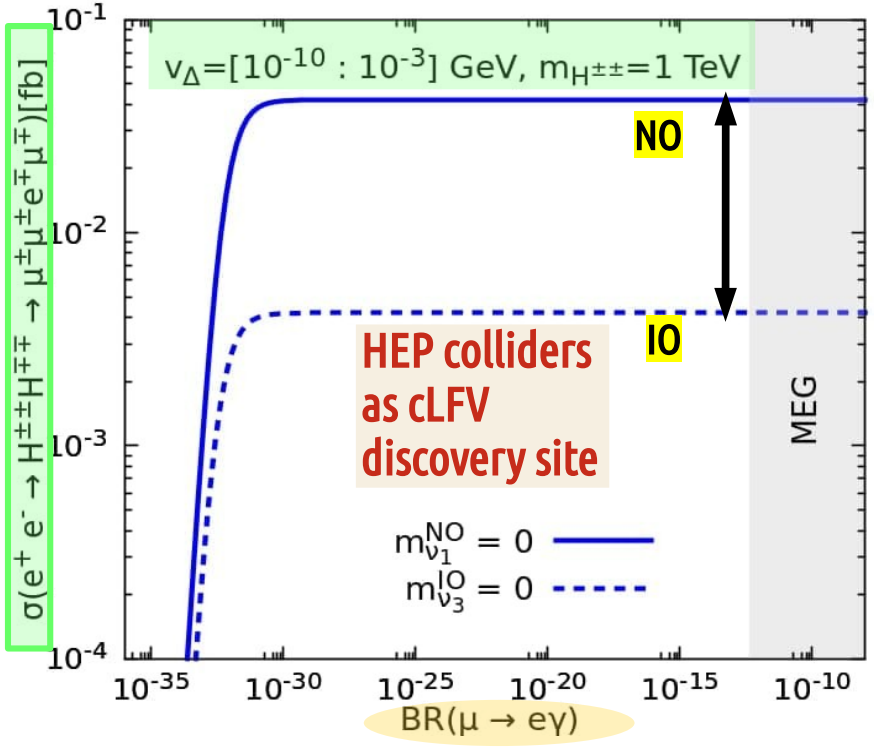
Can be reconstructed from data leading to high-energy tests

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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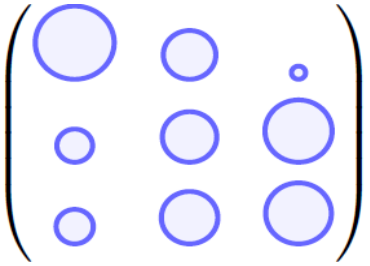
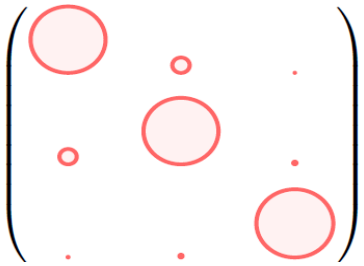
flavour legacy of oscillations

Q/L mixing pattern



versus



Q/L mass hierarchies

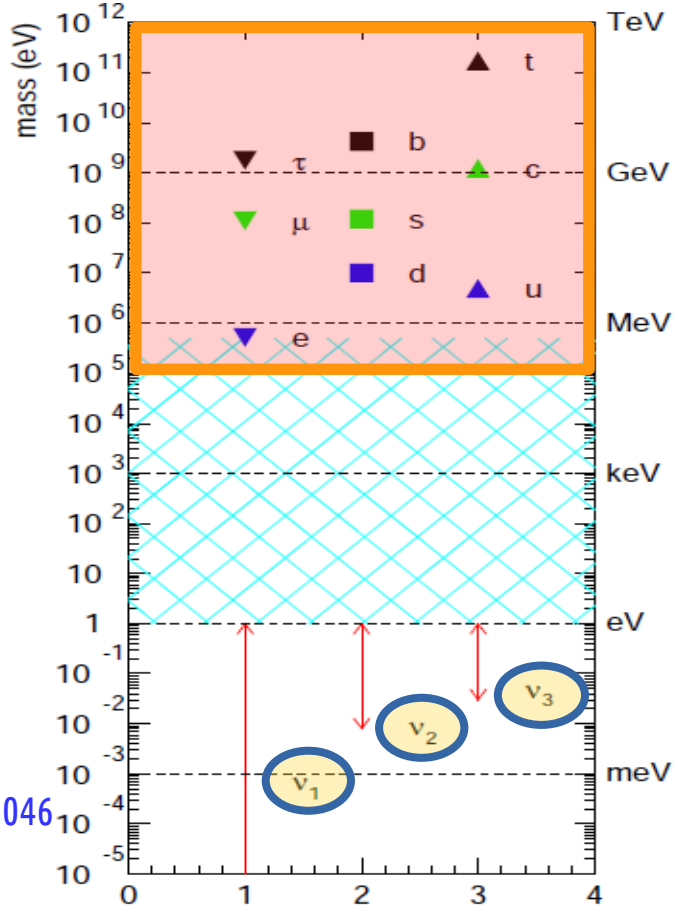
$$\frac{m_\tau}{\sqrt{m_\mu m_e}} \approx \frac{m_b}{\sqrt{m_s m_d}}$$

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

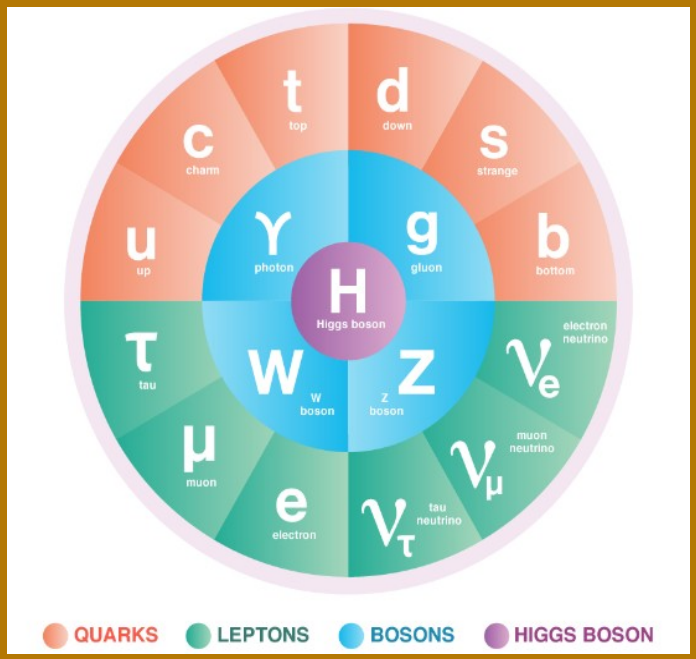
from orbifolds De Anda et al PRD105 (2022) 055030 ,
JHEP10 (2020) 190, PLB 801 (2020) 135195
PRD 101 (2020) 11, 116012 PRD 108 (2023) 3, 035046

modular sym Chen, King, Medina, Valle JHEP 02 (2024) 160



a more radical departure??

HIGGS DISCOVERY DOES NOT CLOSE THE SM



Oscillation discovery brought

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

neutrinos and **flavor**
neutrinos and strong CP problem
neutrinos and **unification**
neutrinos and SM anomalies

DM may seed or mediate neutrino mass generation

pheno imprints of neutrino completions: colliders, cLFV, LNV .. useful neutrino probes

@jwvalle23