neutrinos and the road to new physics

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Interdisciplinary Center for Theoretical Study and Department of Modern Physics
University of Science and Technology of China Hefei, China, February, 2024

ASTROPARTICLES
Astroparticles and High Energy Physics Group

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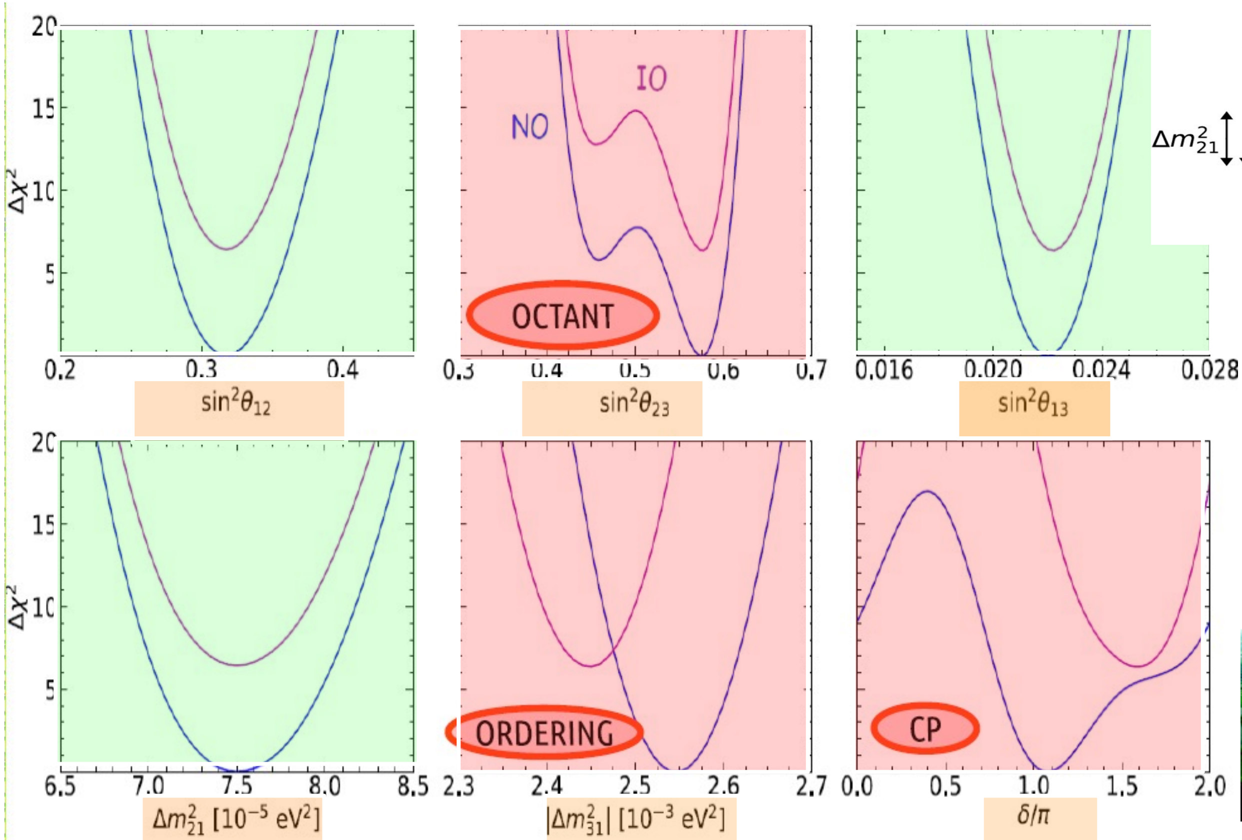
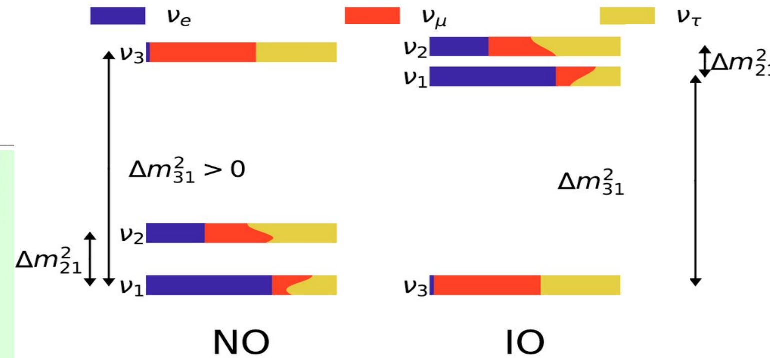
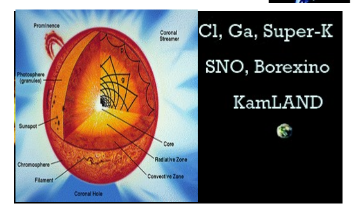
3-neutrino oscillation status

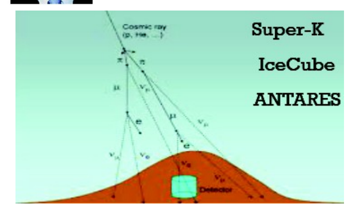
PF de Salas et al JHEP02(2021)071

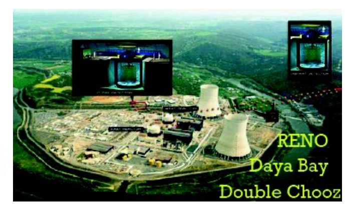
https://zenodo.org/record 4593330#.YFoBVWNKjIo

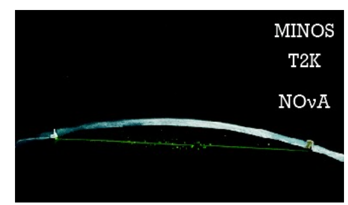












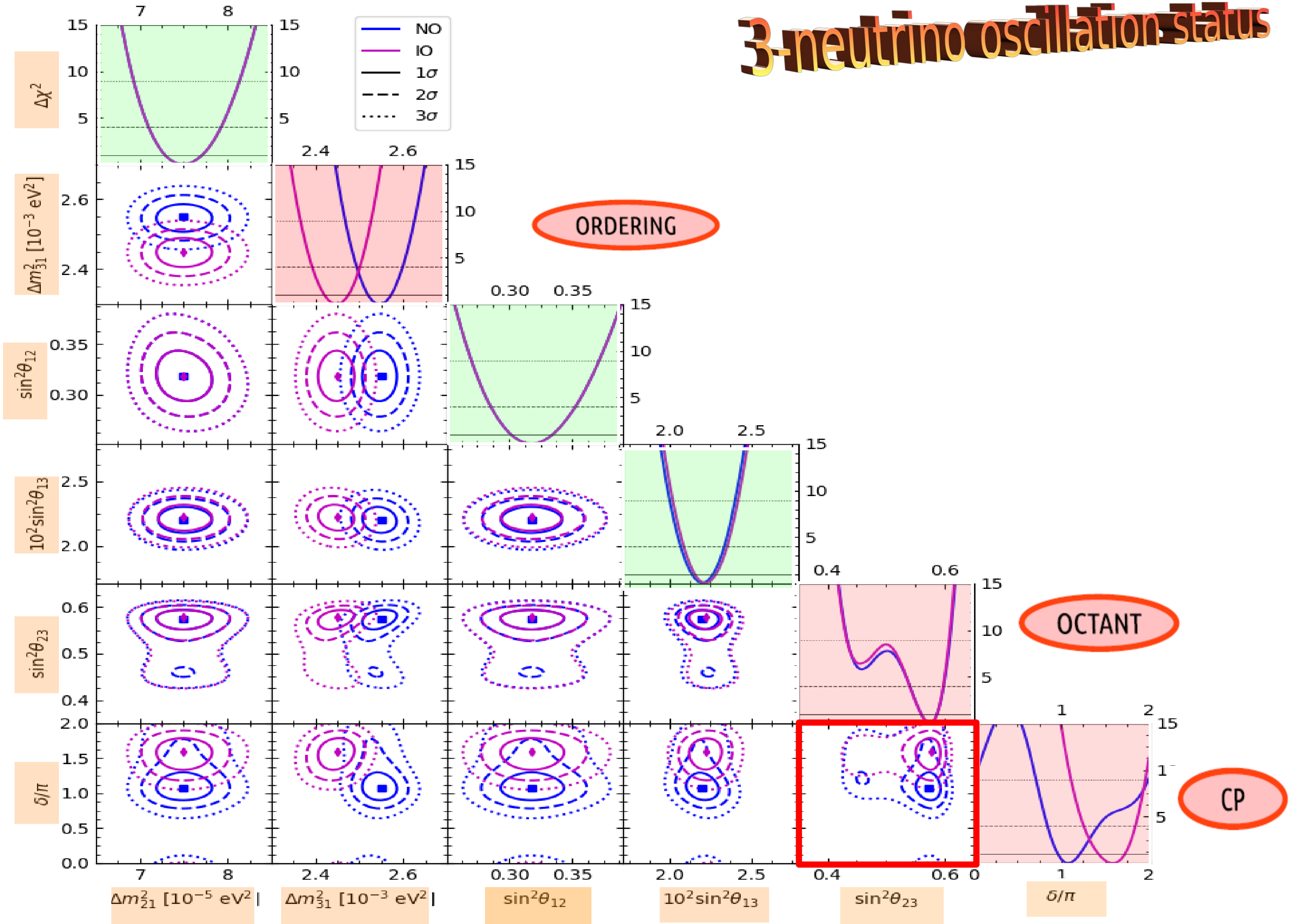
@jwvalle2a

3-neutrino oscillation status

PF de Salas et al JHEP02(2021)071

https://globalfit.astroparticles.es/

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



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

Agreement with NuFit and Bari

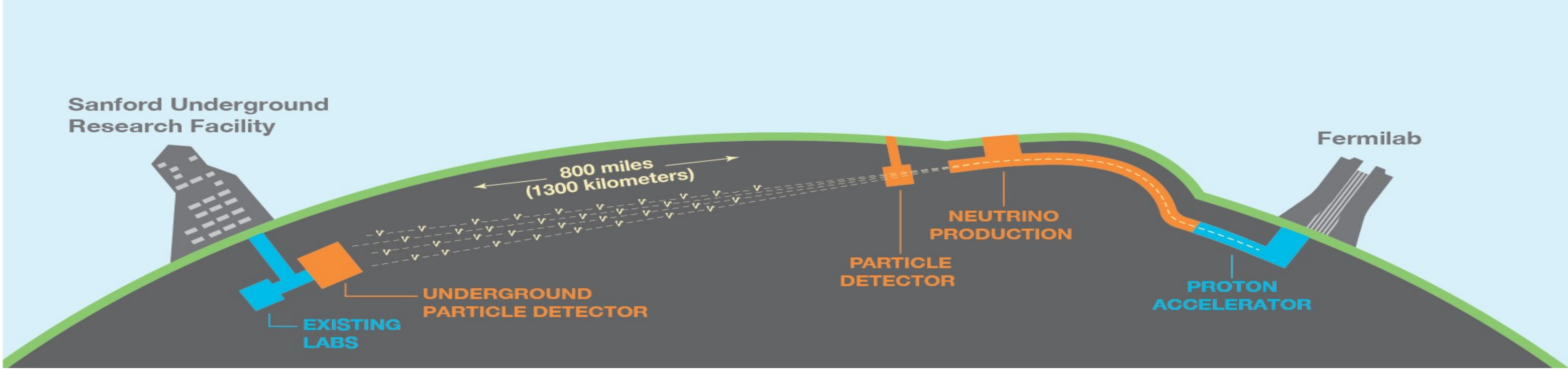
@jwvalle2b

CPV

DUNE 2008.12769

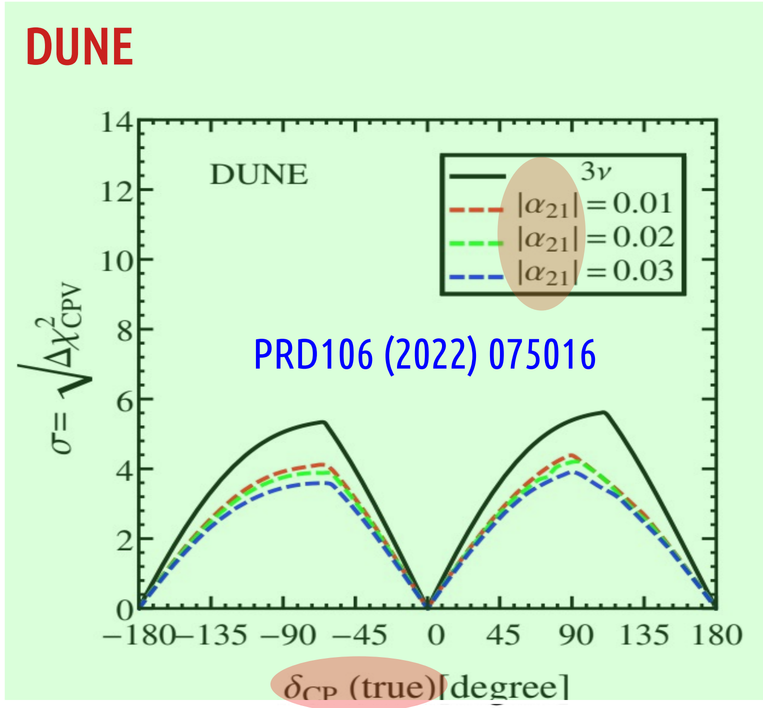
Hyper-K

ESSnuSB



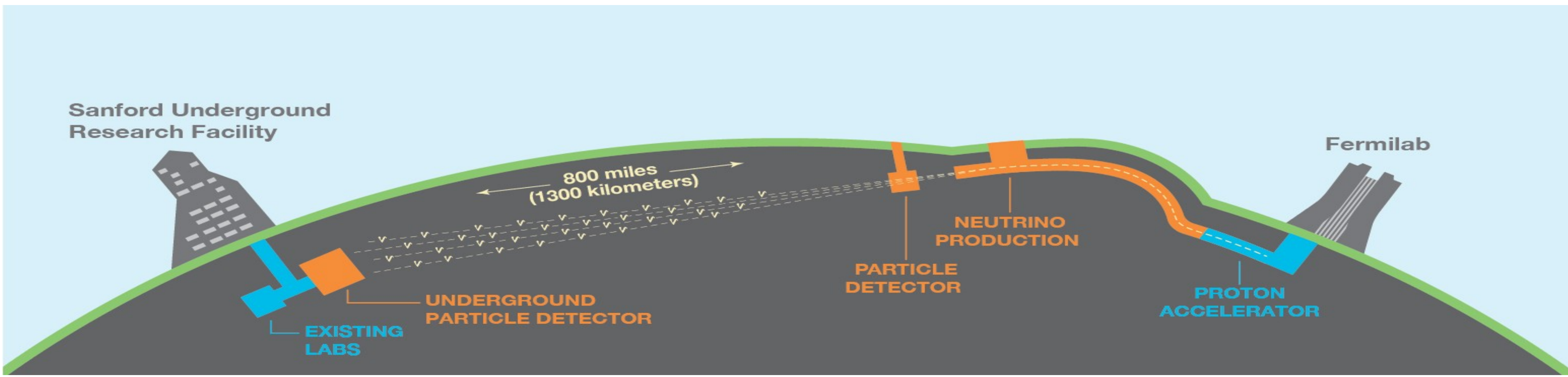
CPV

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



DUNE 2008.12769
Hyper-K
ESSnuSB

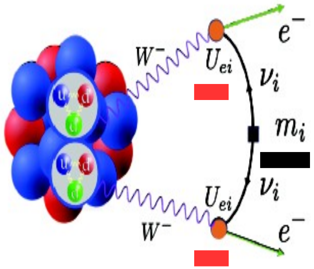
Expected CP discovery Sensitivity: standard 3-nu vs Unitarity violation



@jwvalle3

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

Schechter & JV PRD22 (1980) 2227

Rodejohann, JV Phys.Rev. D84 (2011) 073011

Versus PDG phase convention

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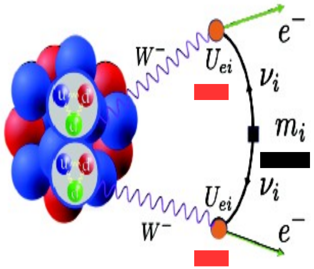

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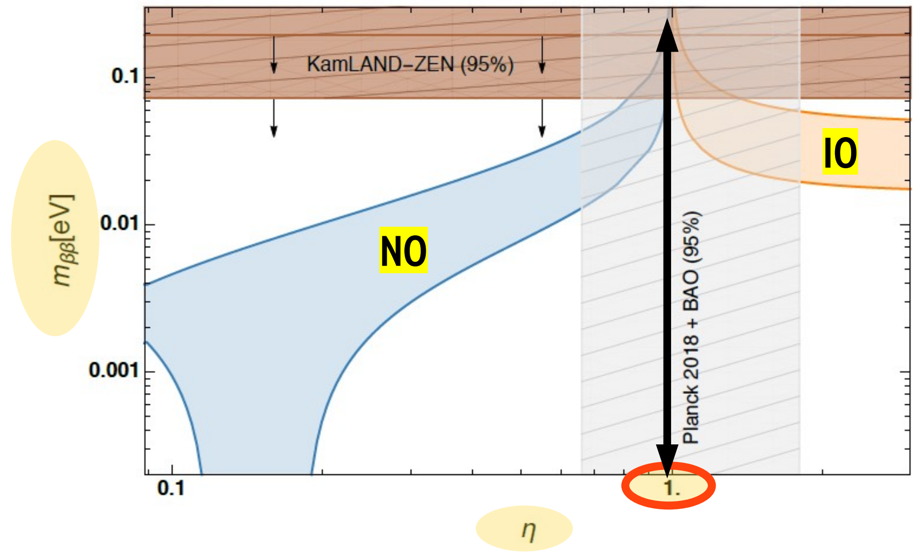

Nearly degenerate Lattanzi et al JHEP 10 (2020) 213

degeneracy parameter

KamLAND-Zen 2203.02139
GERDA 2009.06079

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

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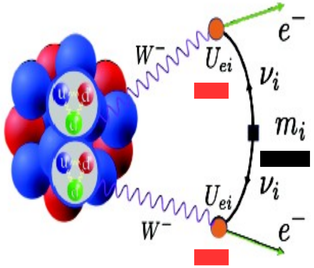

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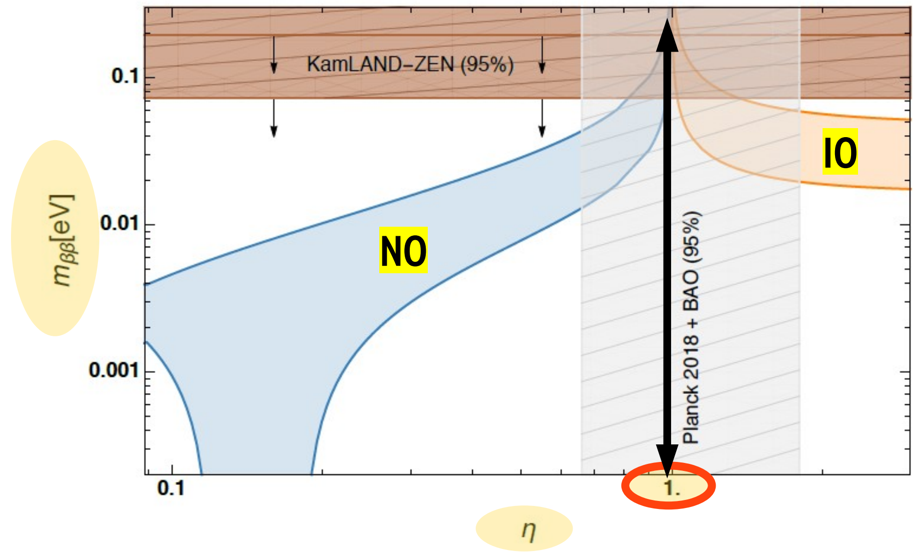


Nearly degenerate Lattanzi et al JHEP 10 (2020) 213

degeneracy parameter

KamLAND-Zen 2203.02139

GERDA 2009.06079

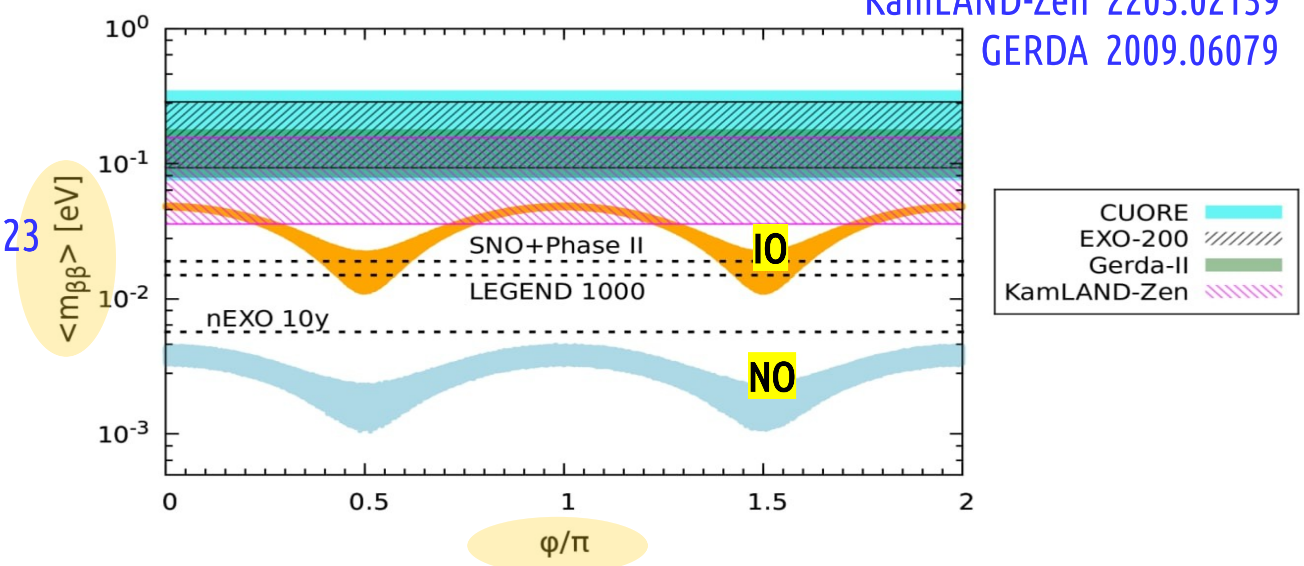
- **One-massless neutrino**

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

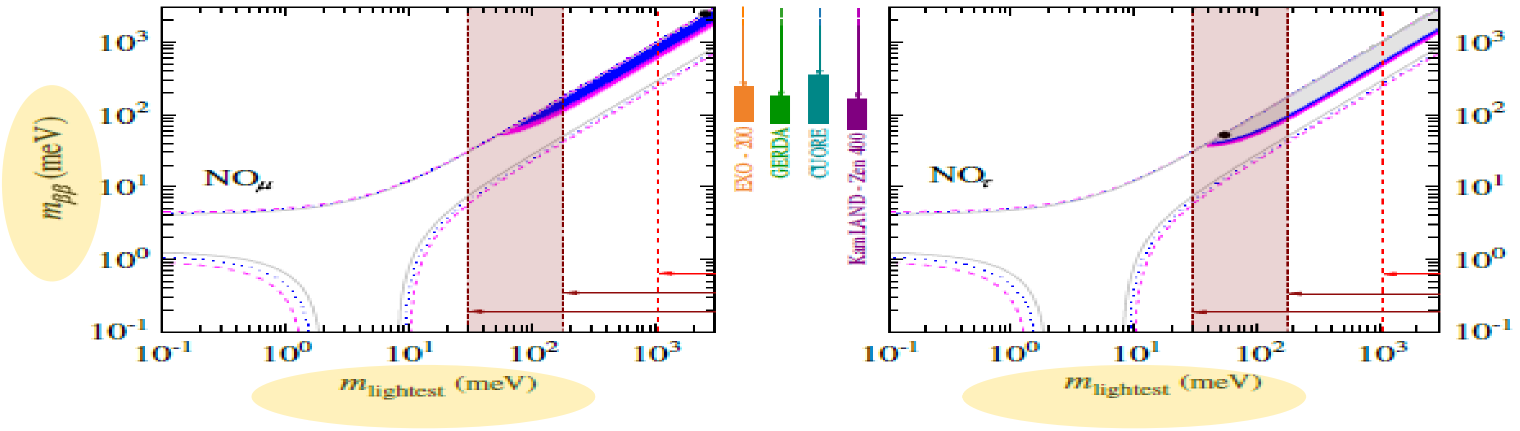
@jwvalle4

- 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



- ## 3-massive case

Lower bounds from oscil. legacy + family symmetries

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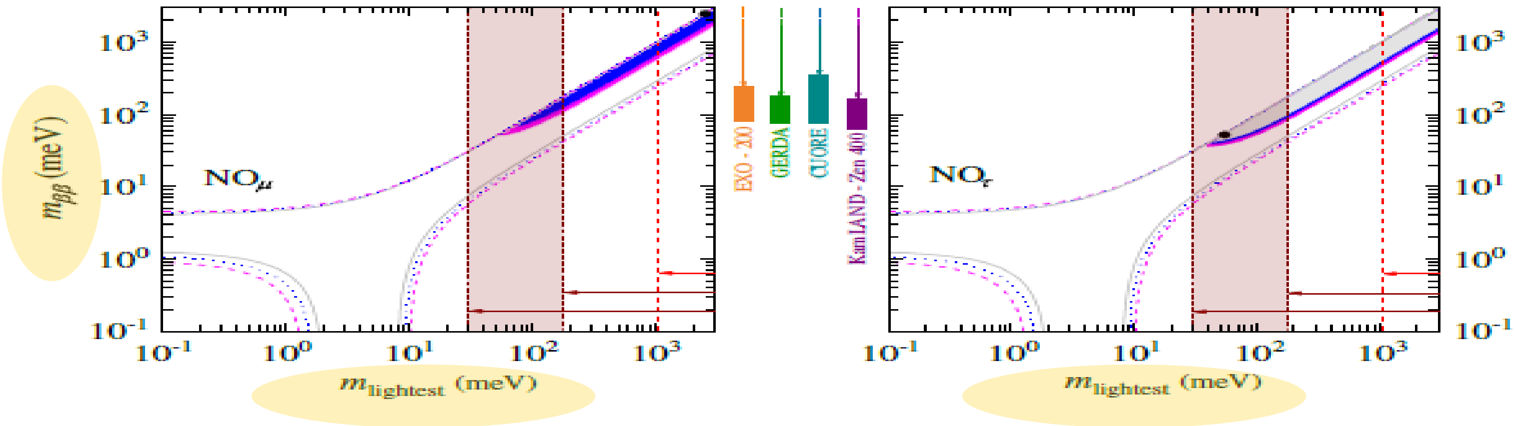
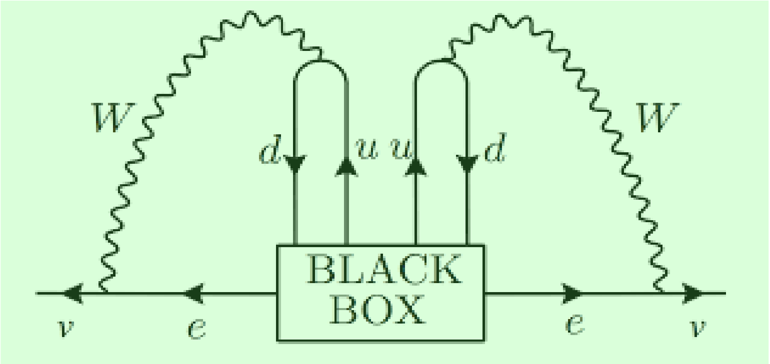
From Barreiros et al JHEP04(2021)249



Significance

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



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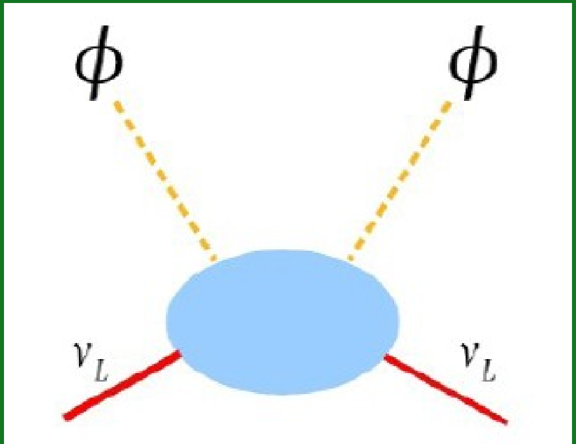
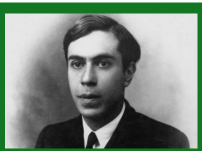
Origin of neutrino mass



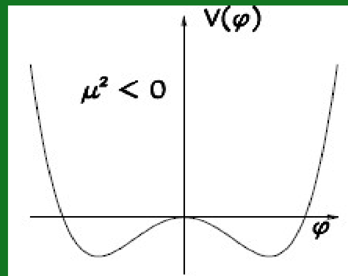


Origin of neutrino mass

stability

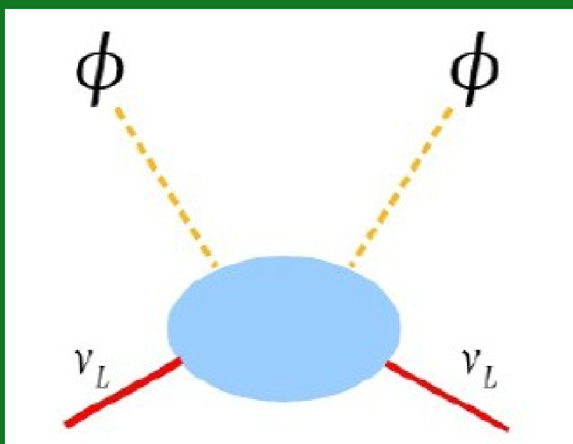
SEESAW
dynamics

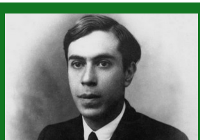
$$v_3 v_1 \sim {v_2}^2$$



Mandal et al PRD101 (2020) 115030

JHEP03(2021)212 & JHEP07(2021) 029





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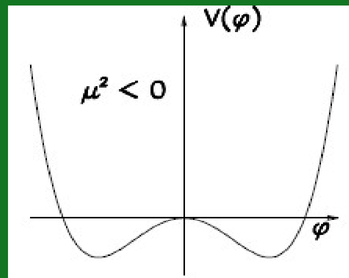

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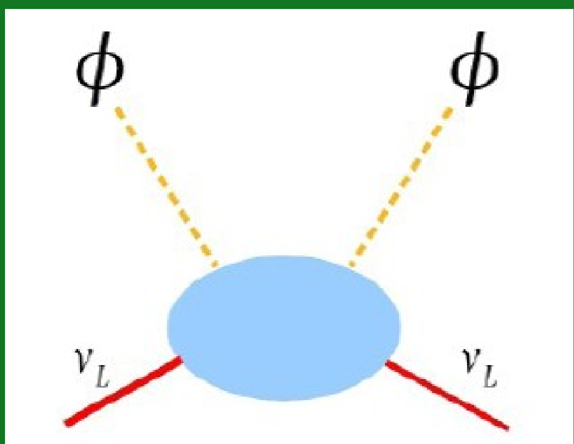
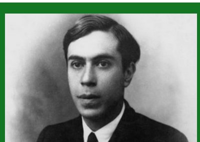
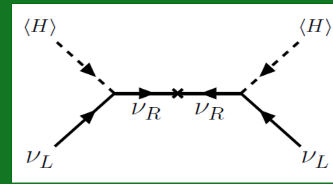






TYPE I

Minkowski 77

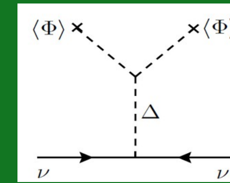
Gellman Ramond Slansky 80

Glashow, Yanagida 79

Mohapatra Senjanovic 80

Lazarides Shafi Weterrich 81

Schechter-Valle 80 & 82



TYPE II

Schechter-Valle 80 & 82

Miranda et al

PLB829 (2022) 137110

PRD105 (2022) 095020

Origin of neutrino mass

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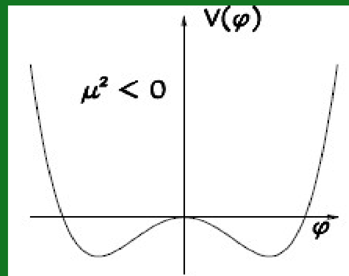

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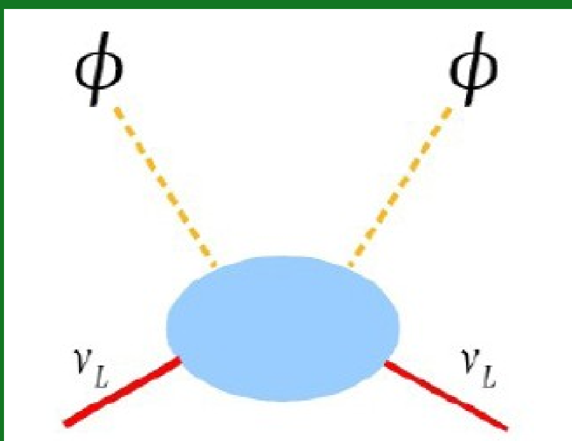

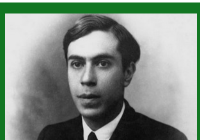

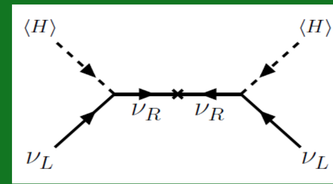

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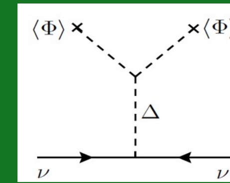

TYPE II

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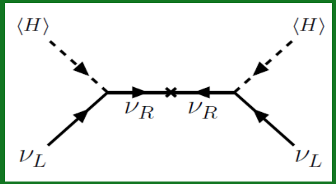
PLB829 (2022) 137110
PRD105 (2022) 095020

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

SM seesaw any # of singlets (3,m)

Origin of neutrino mass



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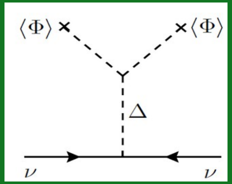

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Schechter-Valle 80 & 82
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PLB829 (2022) 137110
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SEESAW dynamics

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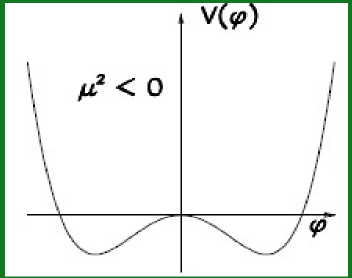
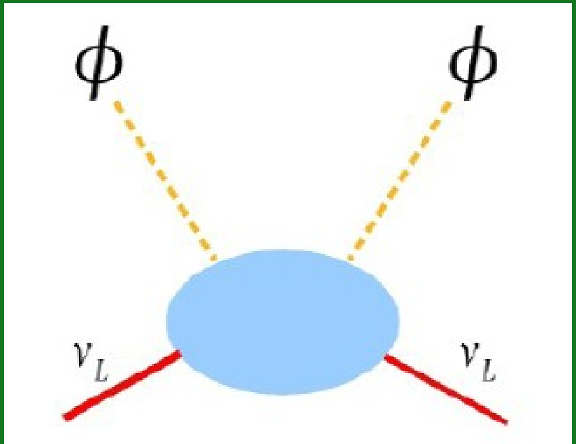
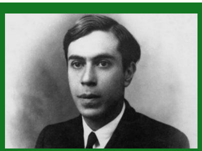
stability



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





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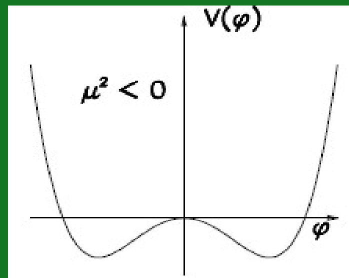
- MISSING PARTNER
  (3,2) min viable type1 seesaw
  (3,1) scoto-seesaw template

$m_{\beta\beta}$

Origin of neutrino mass

stability



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Mandal et al PRD101 (2020) 115030

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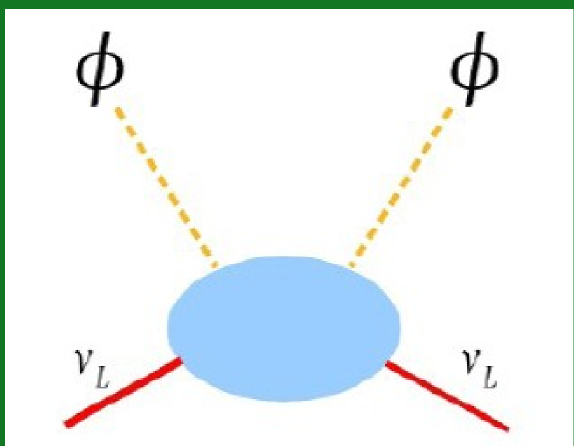

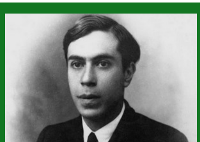

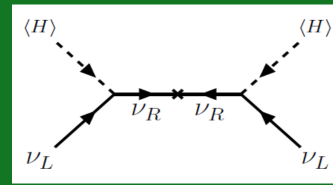

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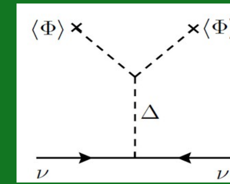

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- MISSING PARTNER
  (3,2) min viable type1 seesaw
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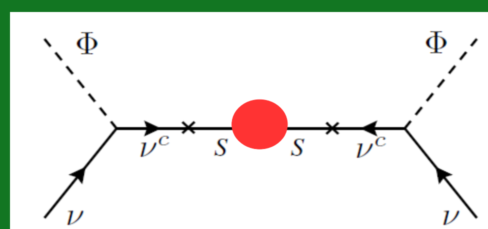
$$m_{\beta\beta}$$

- 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

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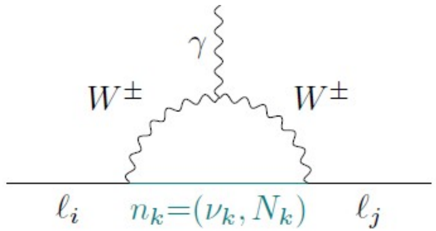
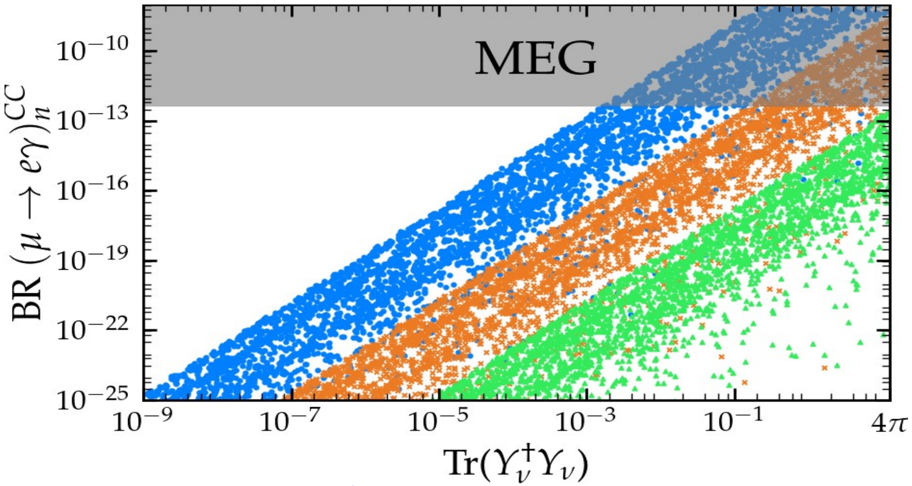
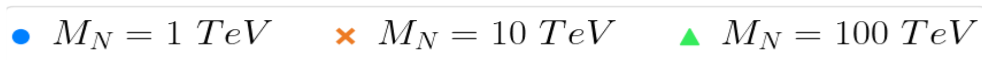
CC Lepton Flavor Violation In low-scale seesaw

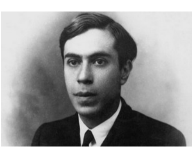
(3,6)



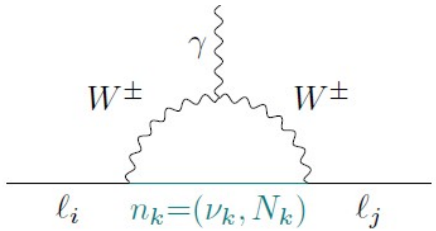


From Batra et al 2305.00994



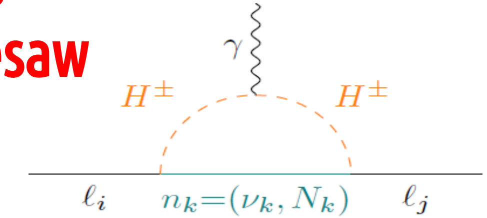


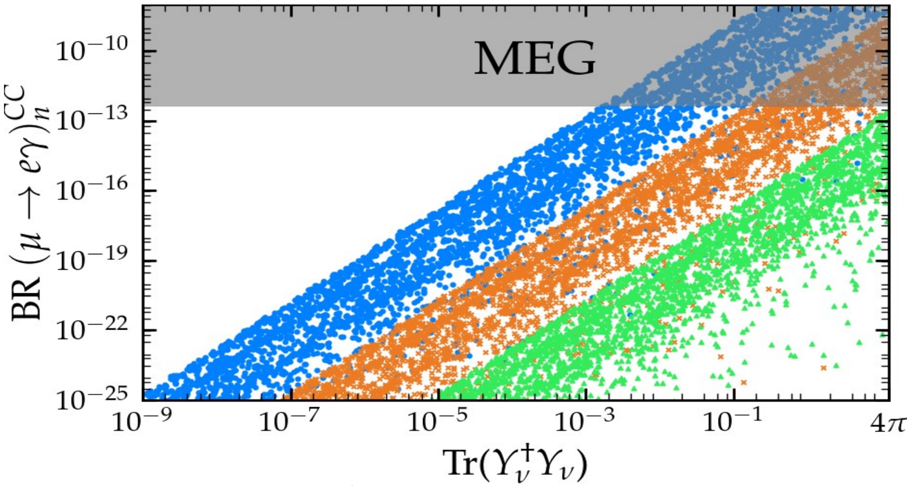
CC Lepton Flavor Violation In low-scale seesaw

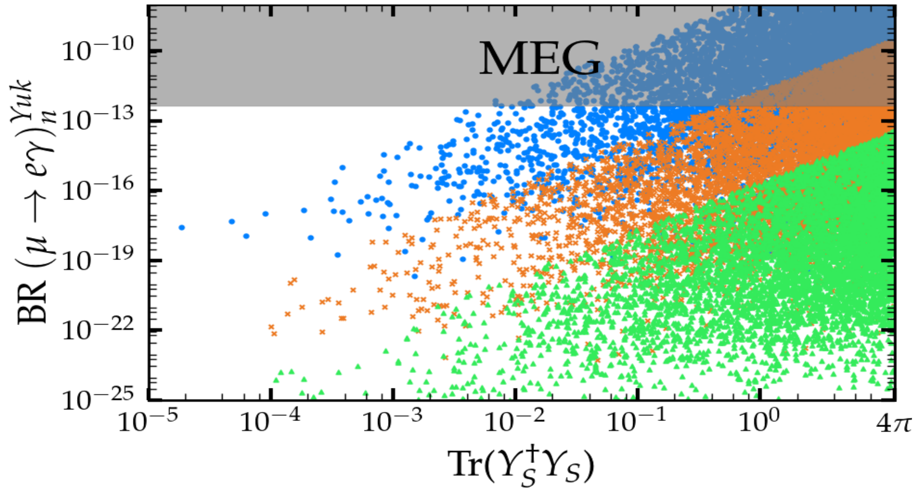


(3,6)

Leptophilic Higgs cLFV in linear seesaw







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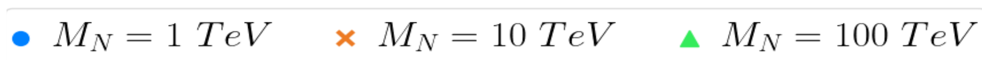
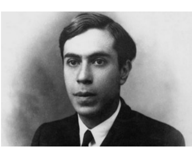


cLFV persists in the massless neutrino limit

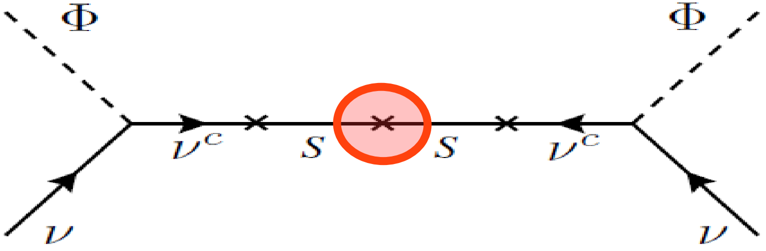
Bernabeu et al B187 (1987) 303-308



@jwvalle7

double protection in low scale seesaw

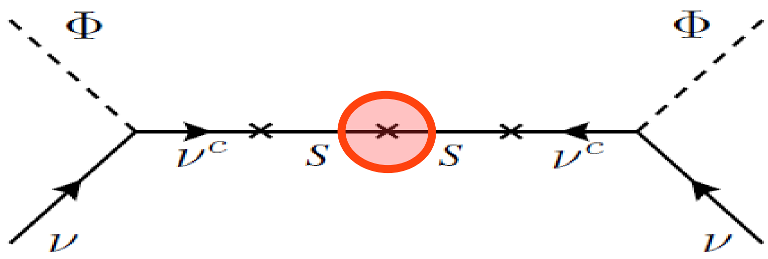
(3,6)



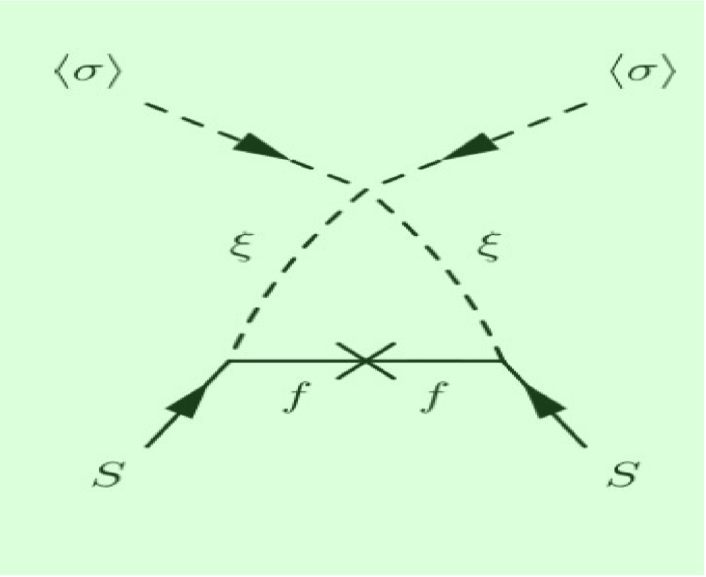
radiative

double protection in low scale seesaw

(3,6)



radiative



is dark matter the seed of neutrino mass?

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

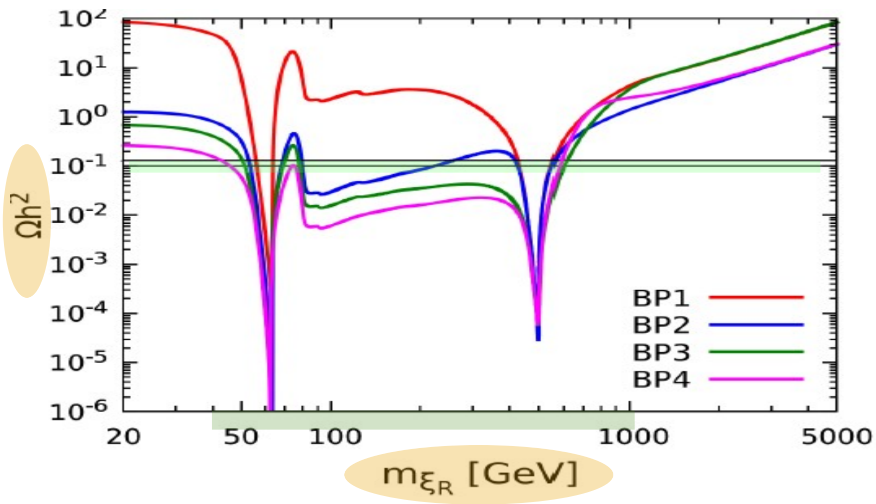
@jwvalle8

dark inverse seesaw

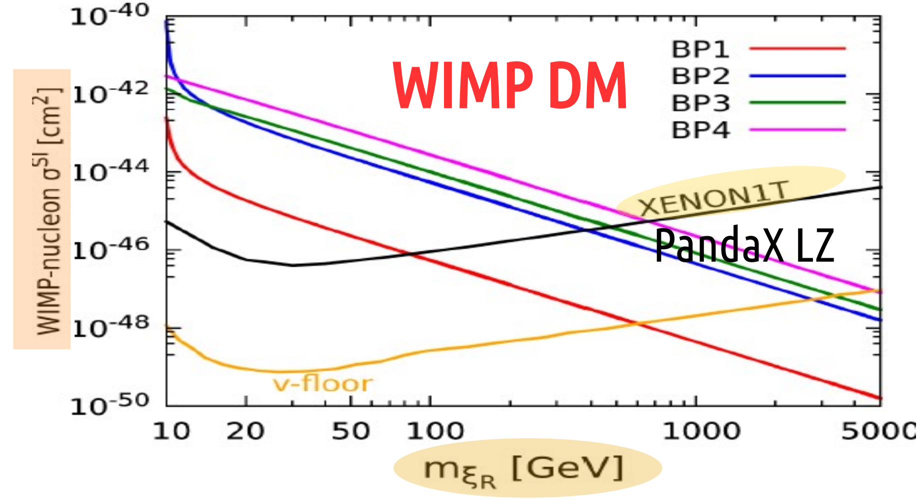
low-scale type-1

LambdaCDM

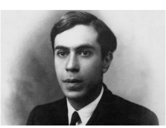
Phys.Lett.B821 (2021) 136609



Xenon1T PhysRevLett.121.111302
PandaX Lux-Zepellin



CLFV



@jwvalle9

low-scale type-1

dark linear seesaw

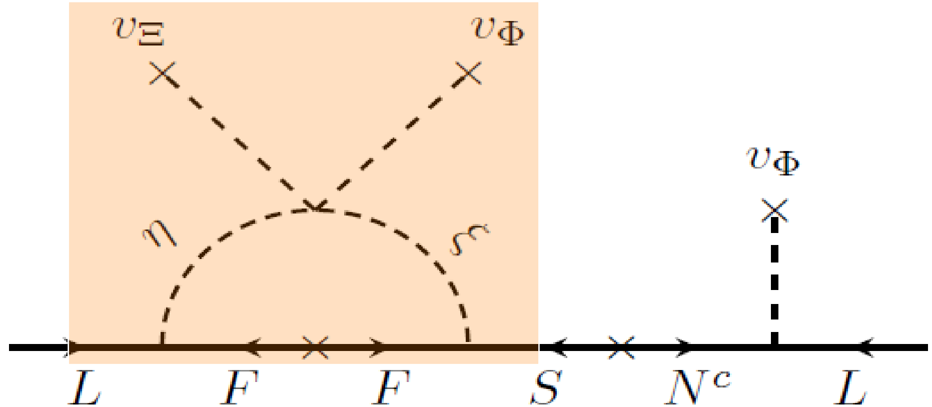
(3,6)

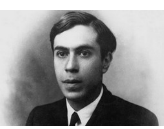
$$M_\nu = \begin{pmatrix} 0_{3\times3} & m_D & \varepsilon \\ m_D^T & 0_{3\times3} & M \\ \varepsilon^T & M & 0_{3\times3} \end{pmatrix}$$

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

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

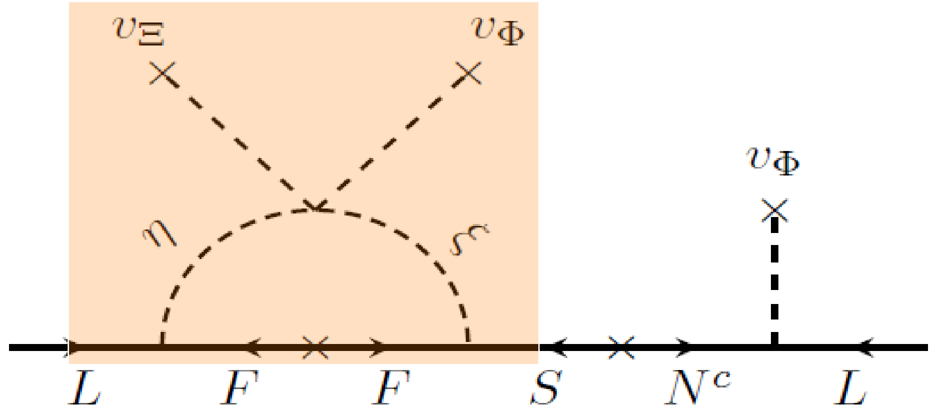
(Also Batra, Camara, Joaquim, 2305.01687)





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

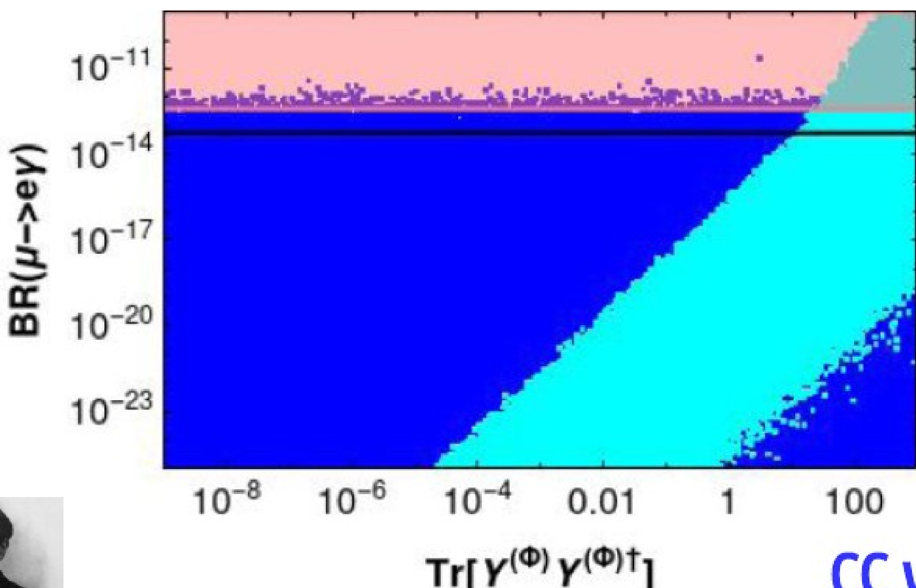
$$M_\nu = \begin{pmatrix} 0_{3\times3} & m_D & \varepsilon \\ m_D^T & 0_{3\times3} & M \\ \varepsilon^T & M & 0_{3\times3} \end{pmatrix}$$

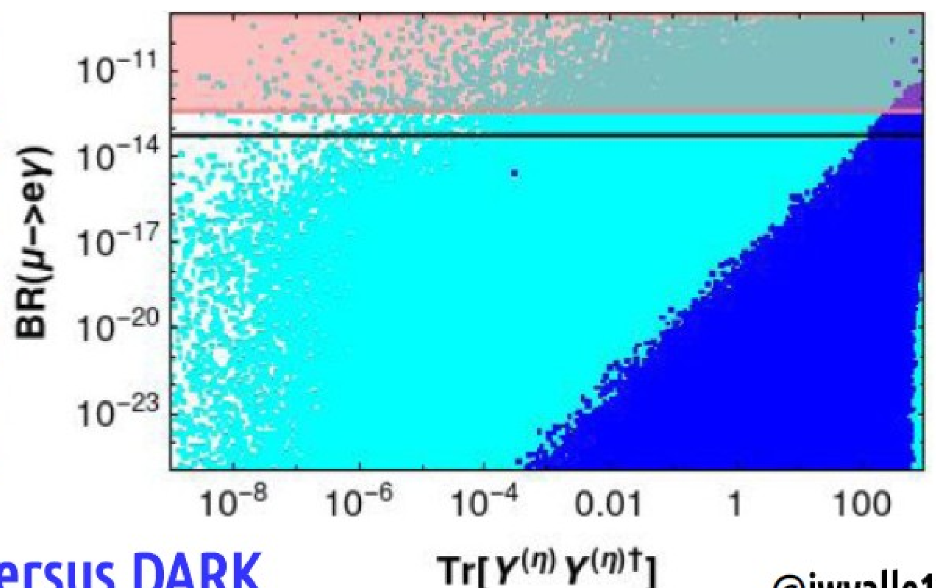


Carcamo, Vishnudath, J.V. JHEP 09 (2023) 046

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

(Also Batra, Camara, Joaquim, 2305.01687)

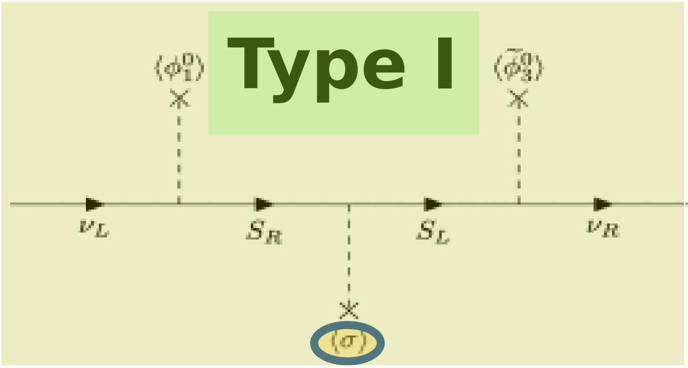


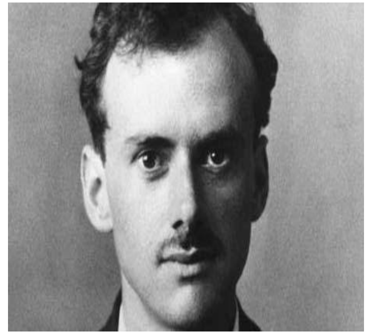


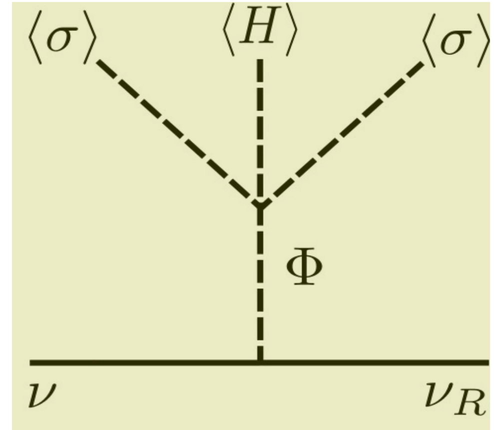
CC versus DARK

@jwvalle10

seesawing a la



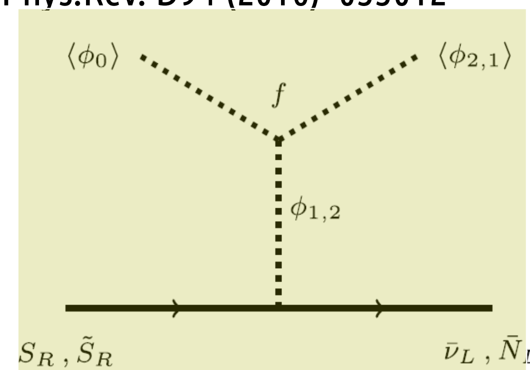




Type II

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

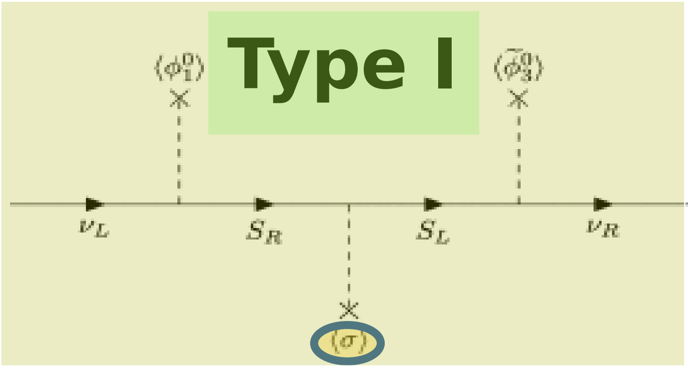
Phys.Rev. D98 (2018) 035009

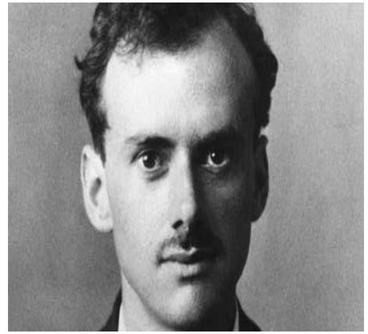
Phys.Lett. B781 (2018) 122-128

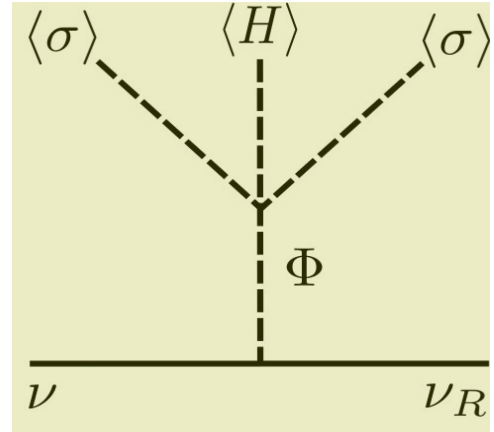
Addazi et al Phys.Lett. B759 (2016) 471-478

Phys.Lett. B755 (2016) 363-366

seesawing a la



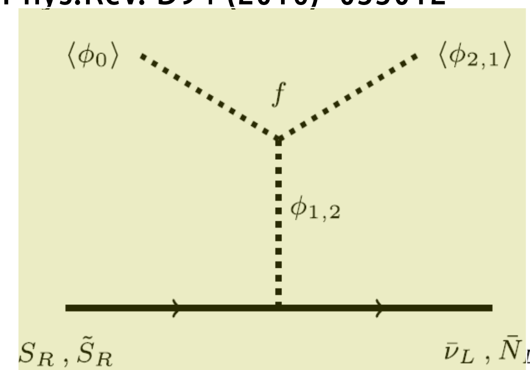




Type II

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



symmetry protecting small neutrino mass

+ Diracness

Peccei-Quinn symmetry

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

SU3L → w

PQ → v_σ

Phys.Lett.B 810 (2020) 135829

Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

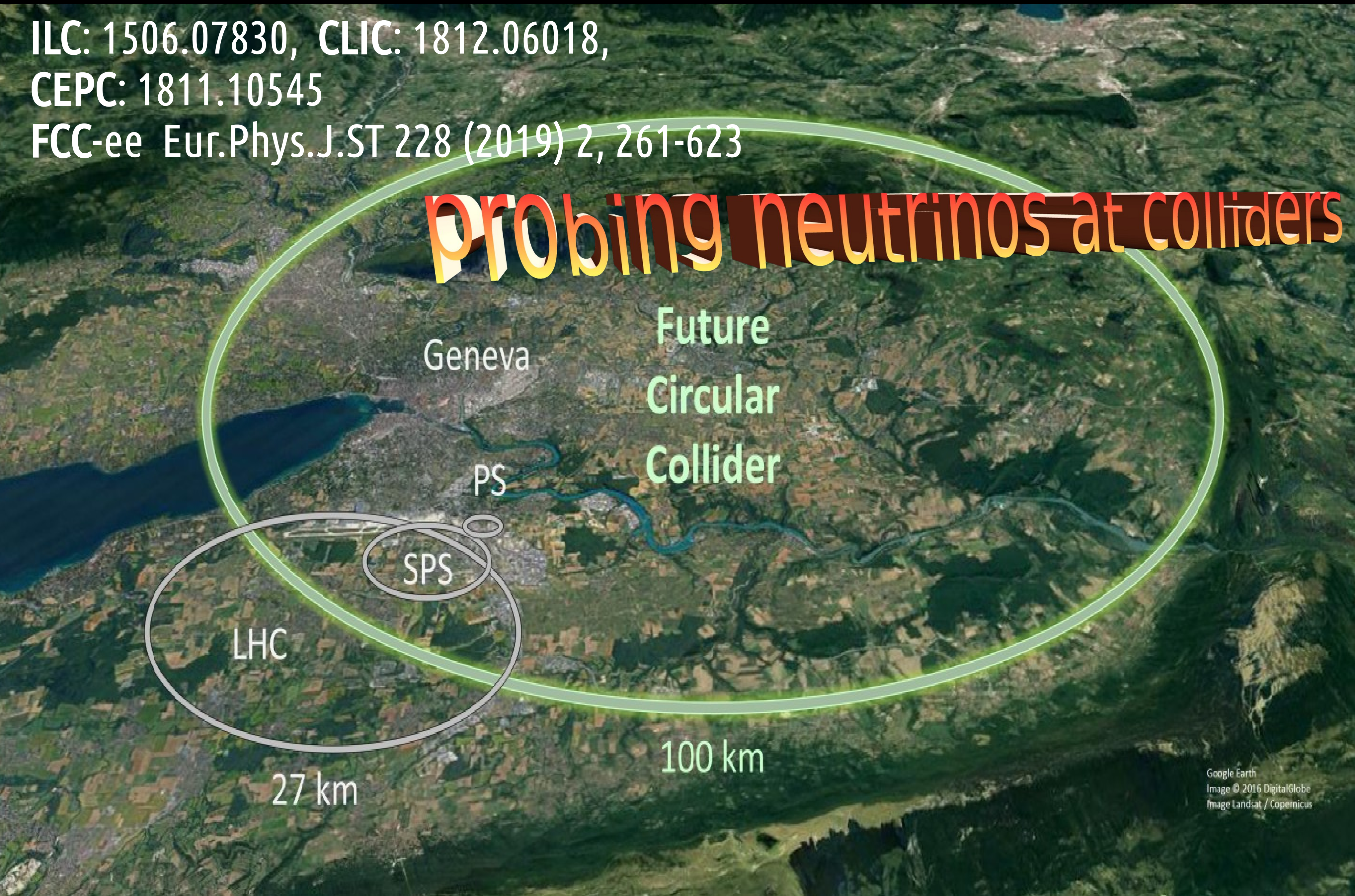
Phys.Rev. D98 (2018) 035009

Phys.Lett. B781 (2018) 122-128

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

Phys.Lett. B755 (2016) 363-366

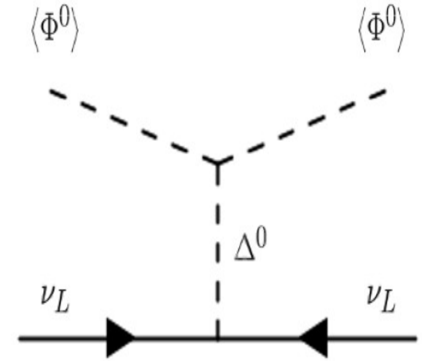
@jwvalle11


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

low-scale type-2

triplet seesaw

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



Can be reconstructed from data leading to high-energy tests

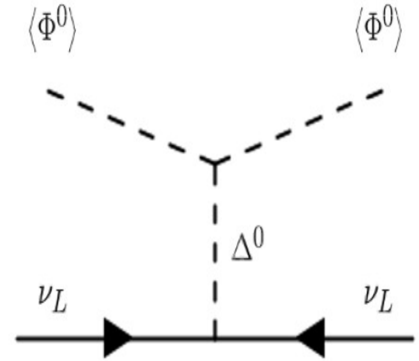
Miranda et al Phys.Rev.D105 (2022) 095020

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

Miranda et al PLB 829 (2022) 137110

low-scale type-2

triplet seesaw

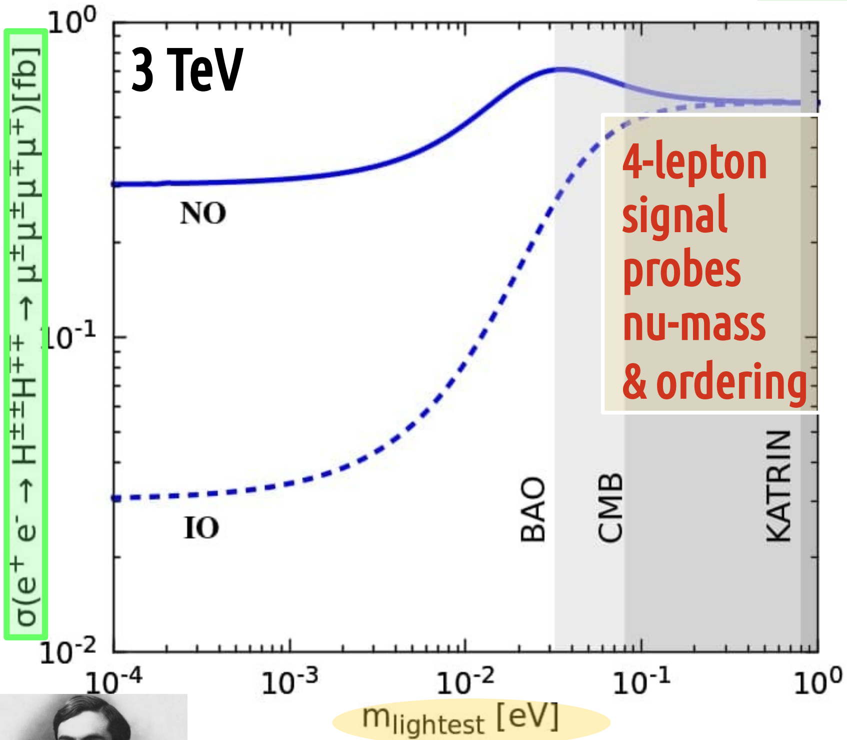


Can be reconstructed from data leading to high-energy tests

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

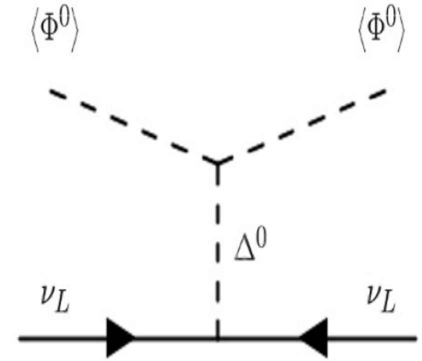
Miranda et al Phys.Rev.D105 (2022) 095020

Miranda et al PLB 829 (2022) 137110



low-scale type-2

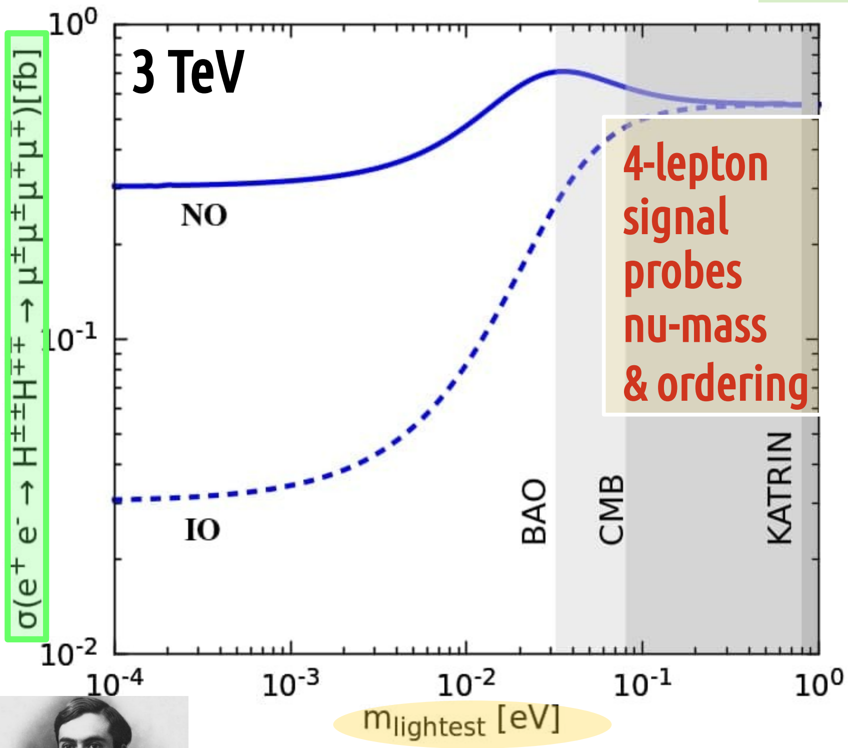
triplet seesaw



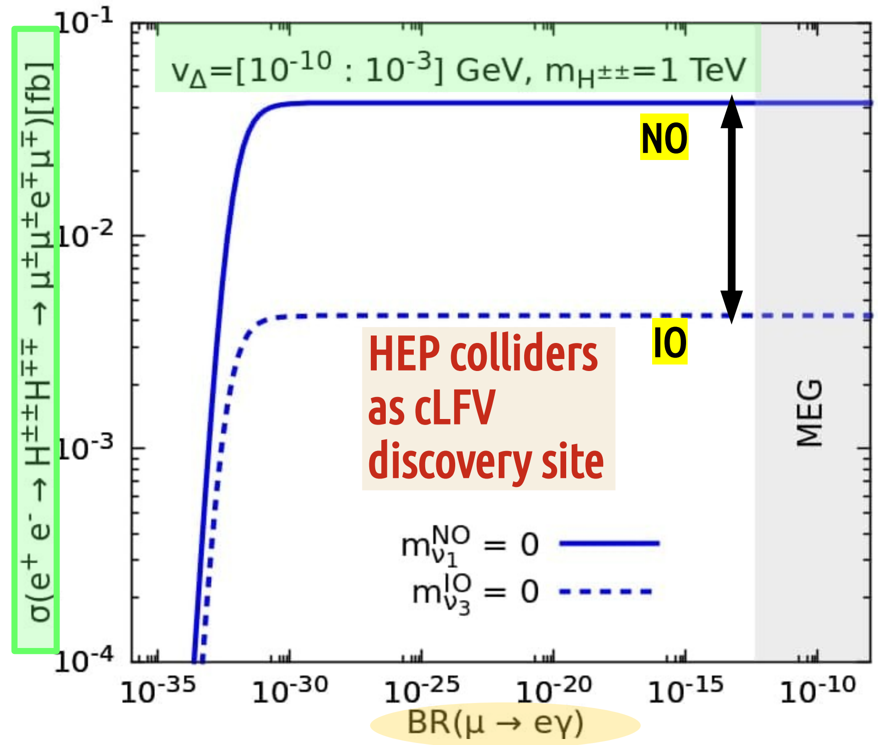
Can be reconstructed from data leading to high-energy tests

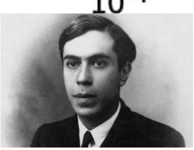
seesaw mediator produced in @ e+e- / pp collisions

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



Miranda et al PLB 829 (2022) 137110





@jwvalle13


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

neutrinos and dark matter

the scotogenic paradigm

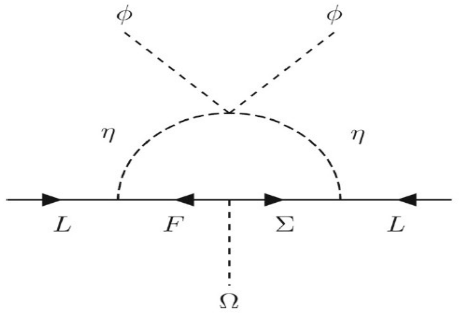
scoto

LOOP

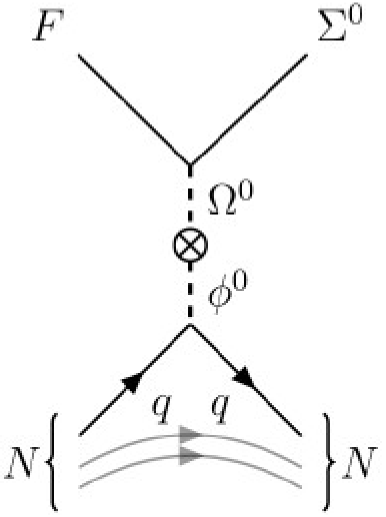
Ma hep-ph/0601225
Tao hep-ph/9603309
Dark-mediated nu-mass loop

generalized scoto DM

Eur. Phys. J. C (2020) 80:908

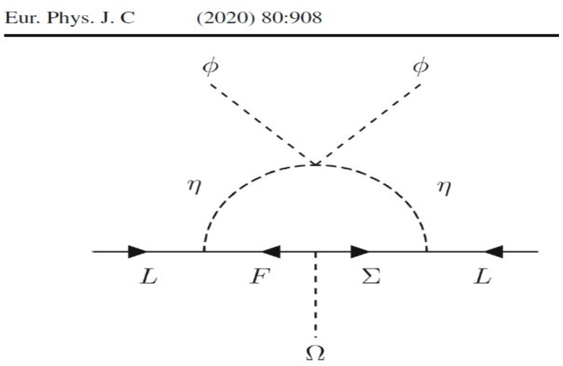


M. Hirsch et al JHEP 10 (2013) 149
A. Merle et al JHEP 07 (2016) 013
Rocha-Moran, Vicente JHEP 07 (2016) 078
Restrepo, Rivera JHEP 04 (2020) 134

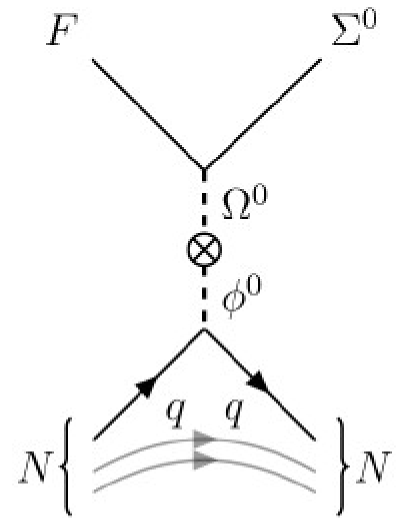


Avila et al Eur.Phys.J.C 80 (2020) 10, 908
Karan, Sadhukhan, Valle JHEP12 (2023) 185

generalized scoto DM

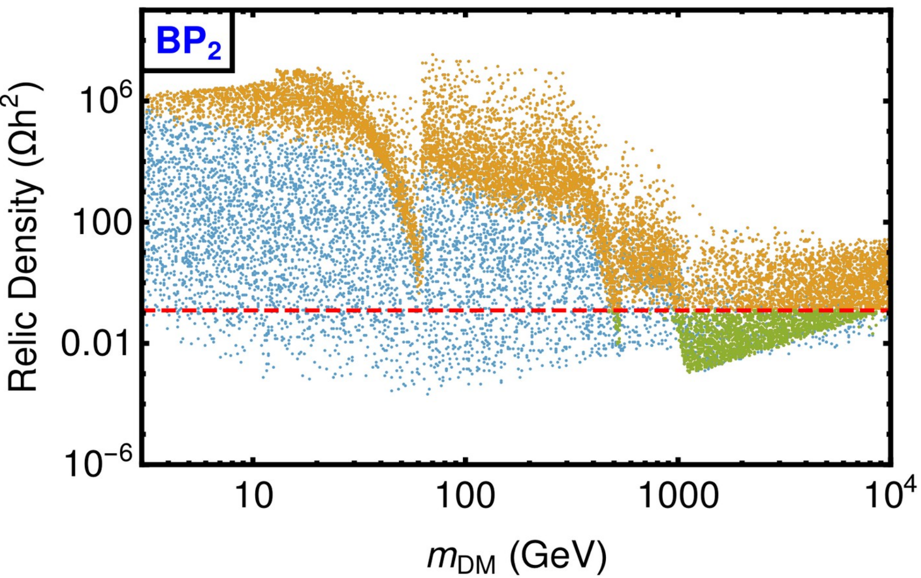


M. Hirsch et al JHEP 10 (2013) 149
A. Merle et al JHEP 07 (2016) 013
Rocha-Moran, Vicente JHEP 07 (2016) 078
Restrepo, Rivera JHEP 04 (2020) 134

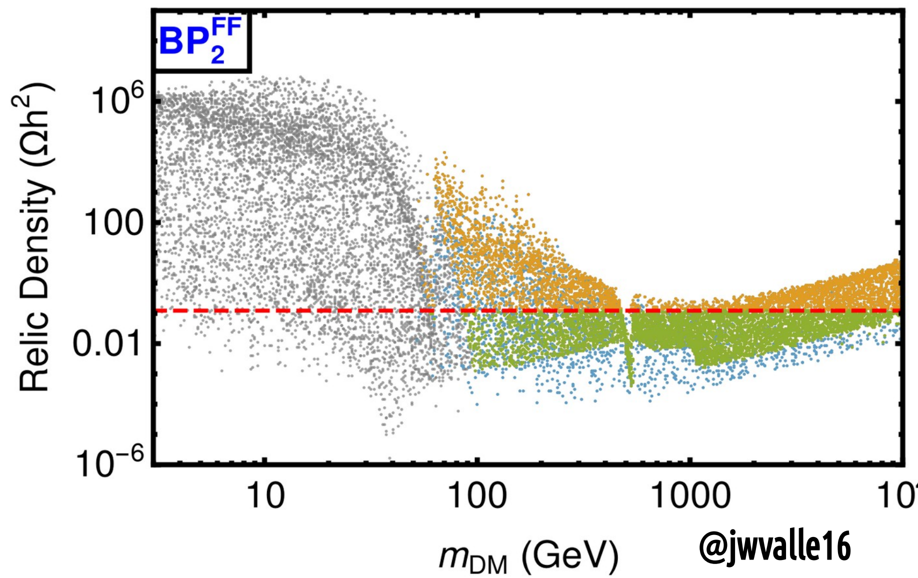


Avila et al Eur.Phys.J.C 80 (2020) 10, 908
Karan, Sadhukhan, Valle JHEP12 (2023) 185

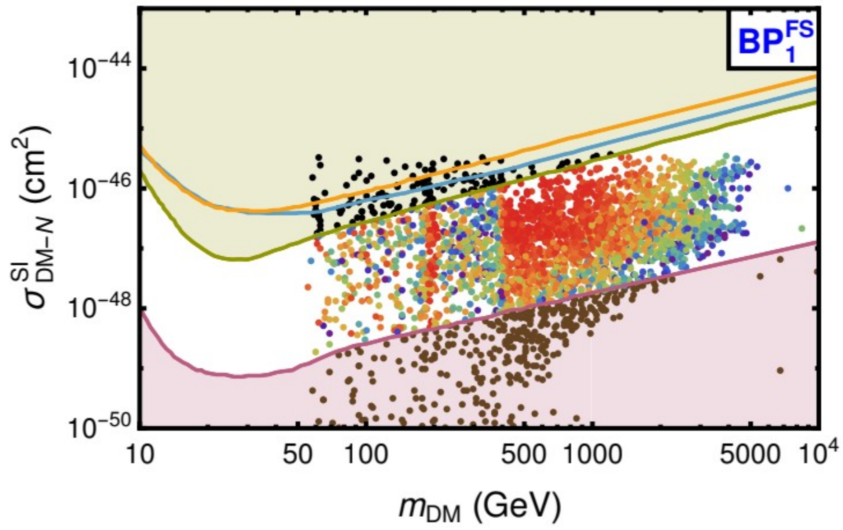
No DM coannihilation:



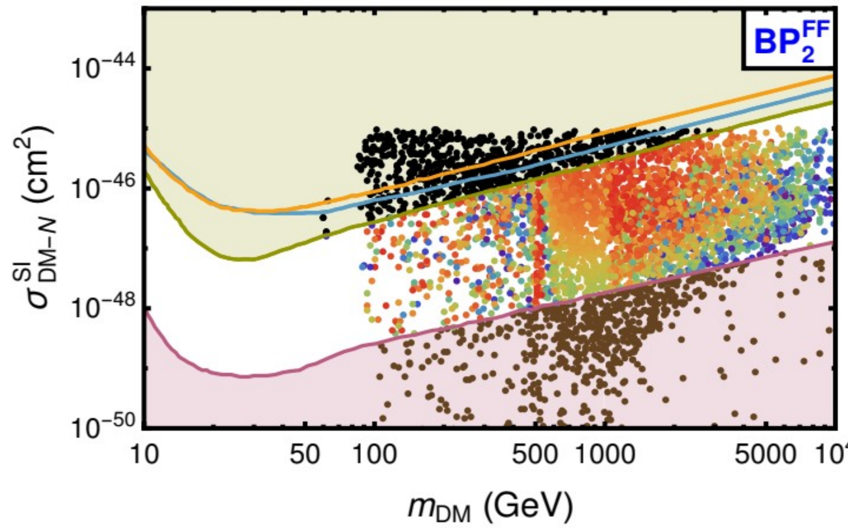
With DM coannihilations



@jwvalle16

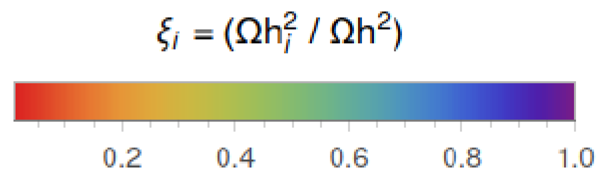


Higher v_Ω (4 GeV): Fermion-Scalar Coannihilation



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]



Karan, Sadhukhan, Valle JHEP12 (2023) 185

DBD lower bound

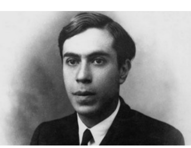
scoto seesaw

LOOP

TREE

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

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

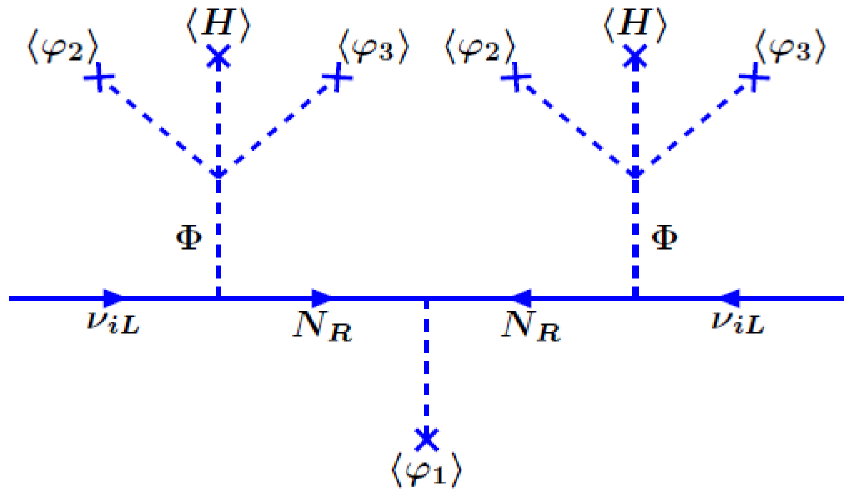


Atm neutrinoseesaw scale

Leite, Sadhukhan, Valle 2307.04840

Tiny induced leptophilic higgs vev
Allows for a lower seesaw scale

(3,3)



Atm neutrinoseesaw scale

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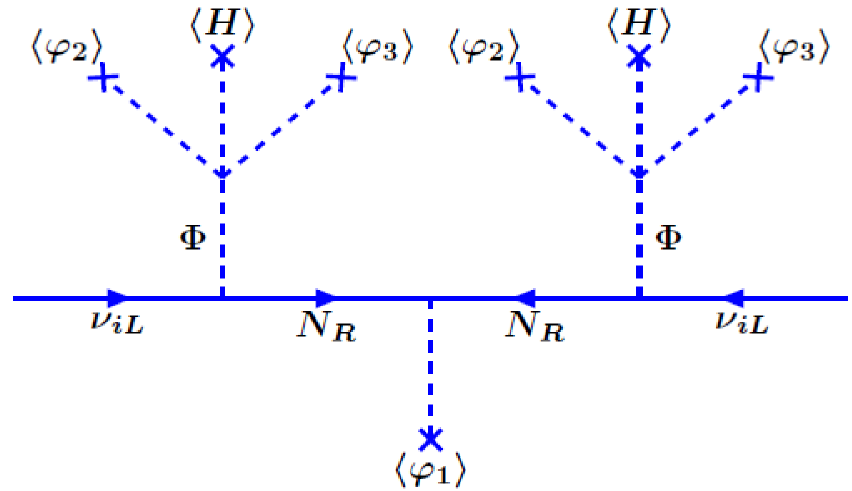
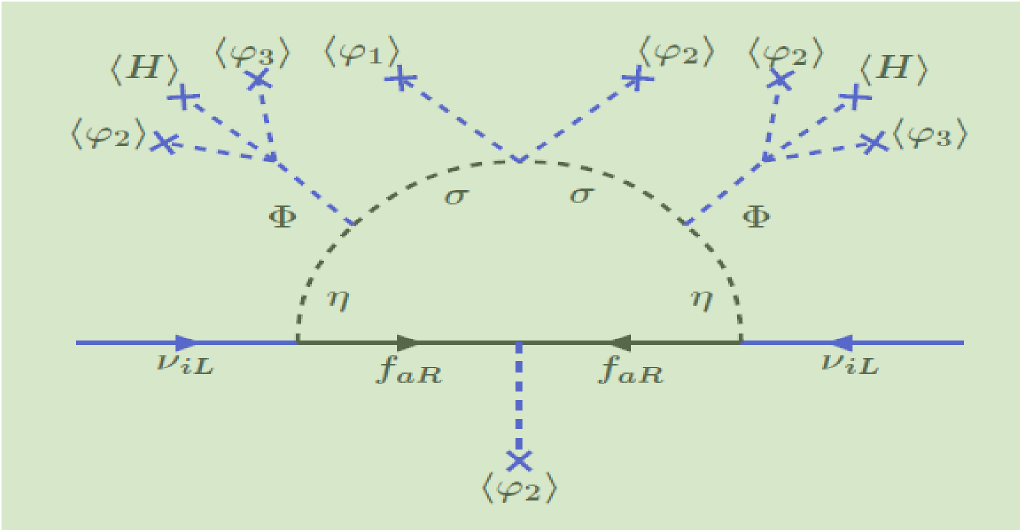
Tiny induced leptophilic higgs vev
Allows for a lower seesaw scale

(3,3)



solar scotoscale

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

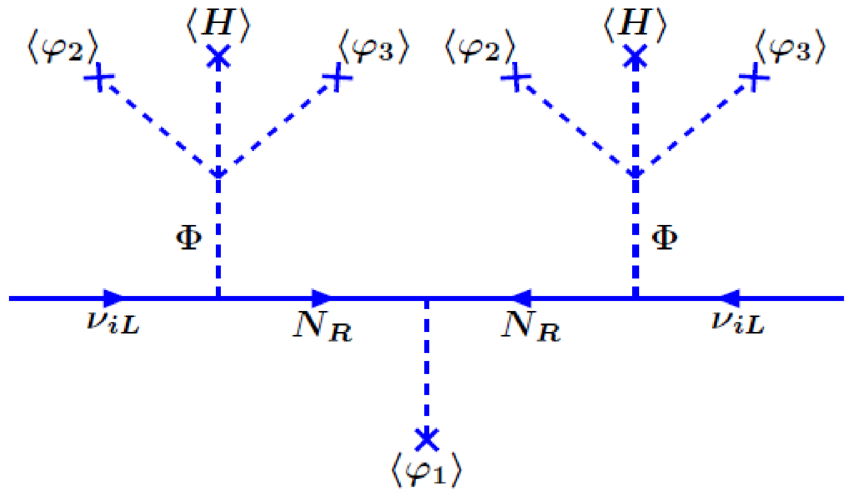


Atm neutrinoseesaw scale

Leite, Sadhukhan, Valle 2307.04840

Tiny induced leptophilic higgs vev
Allows for a lower seesaw scale

(3,3)



Dynamical scoto seesaw

Drell-Yan N_R pair production

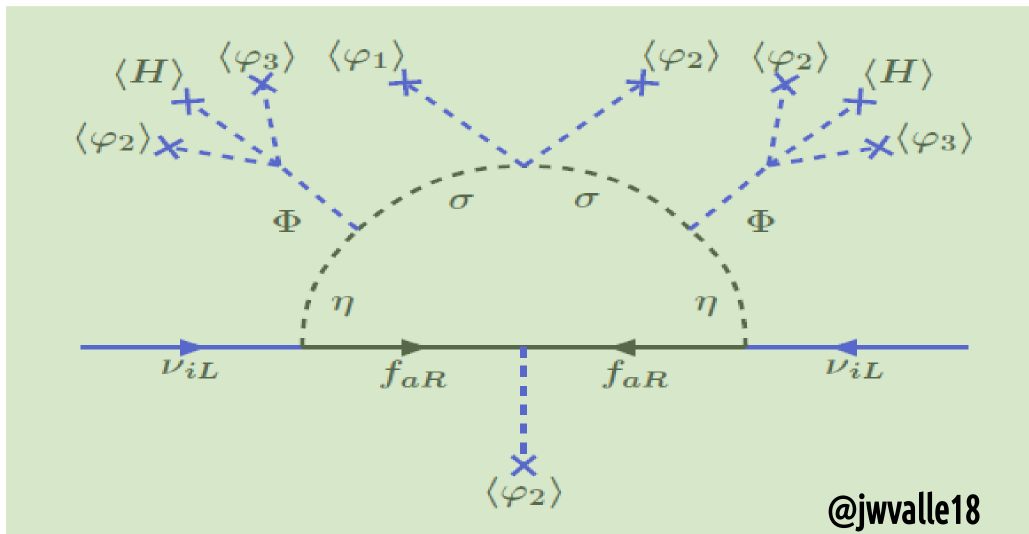
LOOP

TREE

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

solar scoto scale

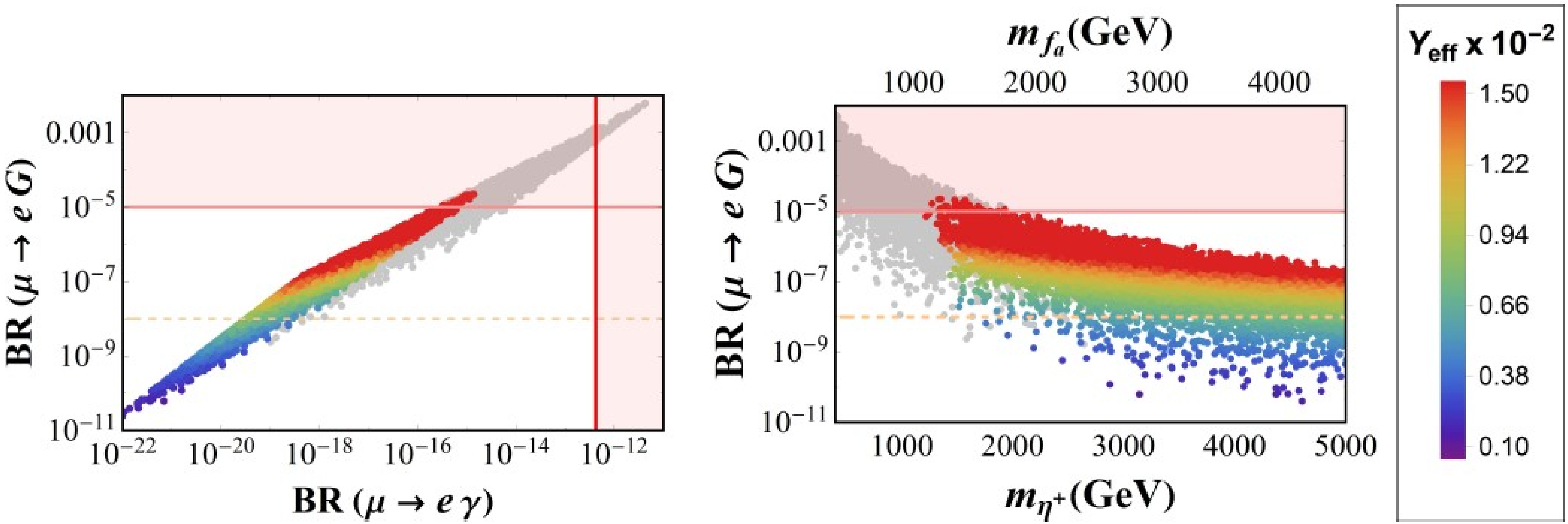
$B-L$ charges $(f_{1R}, f_{2R}, N_R) \sim (-4,-4,5)$



Leite, Sadhukhan, Valle 2307.04840

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

CLFV

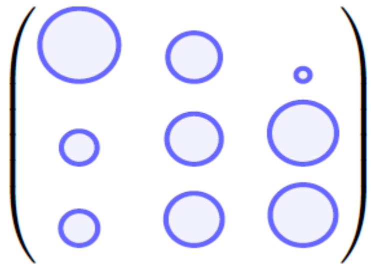


@jwvalle19

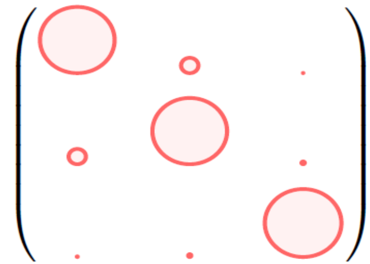
neutrinos and the flavor problem

flavour legacy of oscillations

Q/L mixing pattern

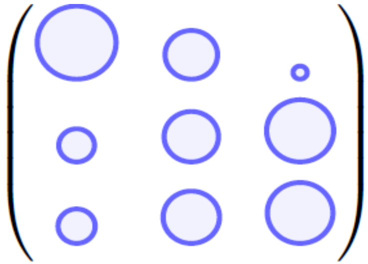


versus

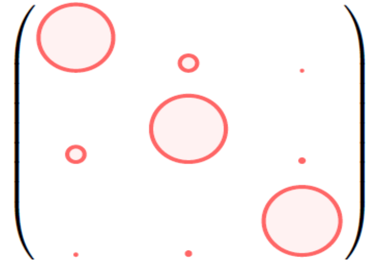


flavour legacy of oscillations

Q/L mixing pattern



versus



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

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

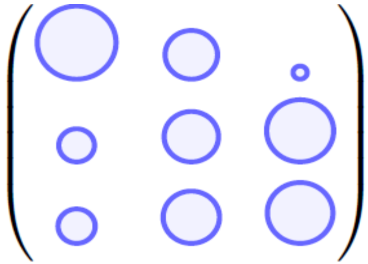
from orbifolds De Anda et al PRD105 (2022) 055030 ,

JHEP10 (2020) 190, PLB 801 (2020) 135195

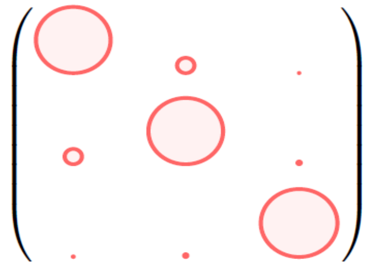
PRD 101 (2020) 11, 116012 and 2212.09174

flavour legacy of oscillations

Q/L mixing pattern

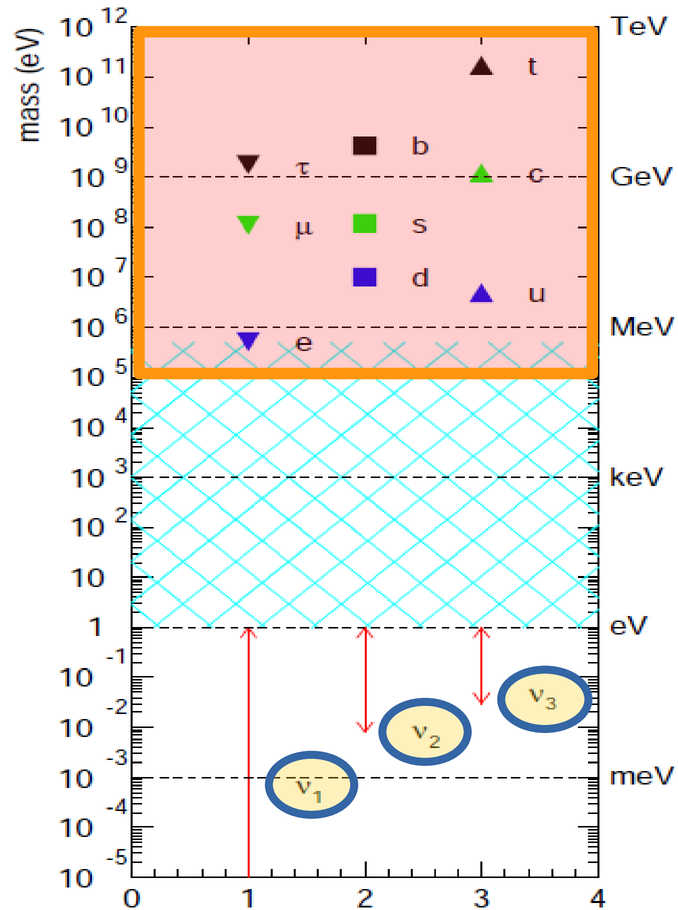


versus



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

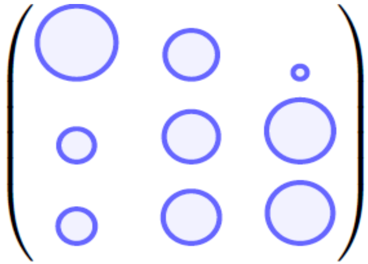
from orbifolds De Anda et al PRD105 (2022) 055030 ,

JHEP10 (2020) 190, PLB 801 (2020) 135195

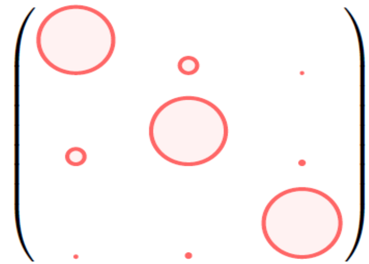
PRD 101 (2020) 11, 116012 and 2212.09174

flavour legacy of oscillations

Q/L mixing pattern



versus



Q/L mass hierarchies

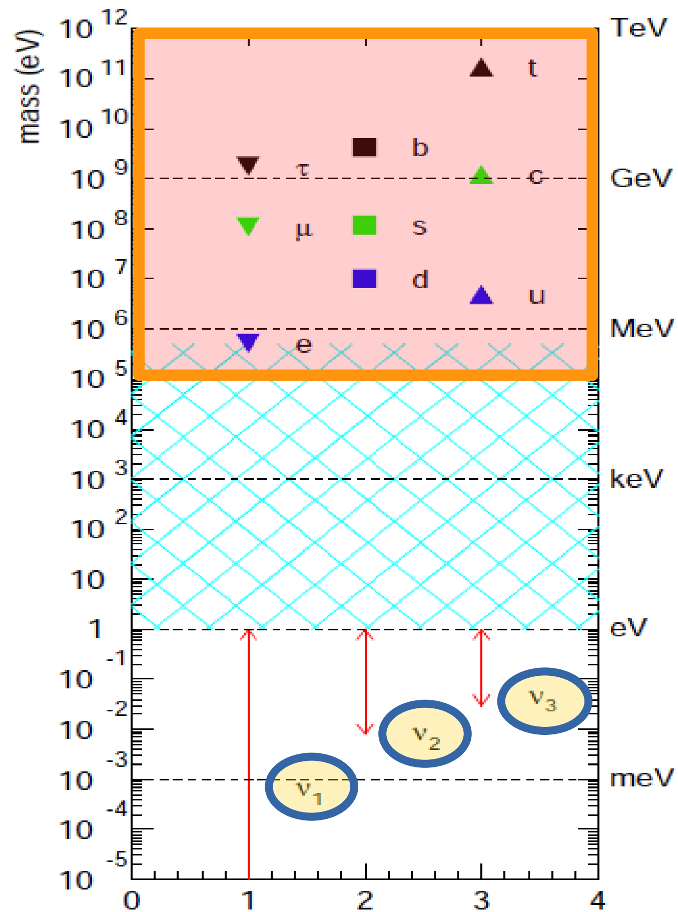
$$\frac{m_\tau}{\sqrt{m_\mu m_e}} \approx \frac{m_b}{\sqrt{m_s m_d}}$$

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

modular sym Chen, King, Medina, Valle 2312.09255



a more radical departure??

@jwvalle21

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’

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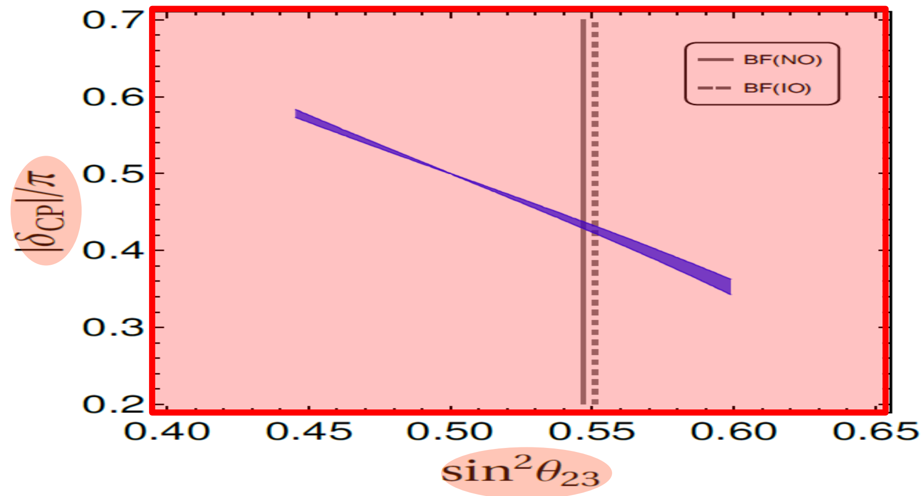
TM mixing pattern predicted from T'

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

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)



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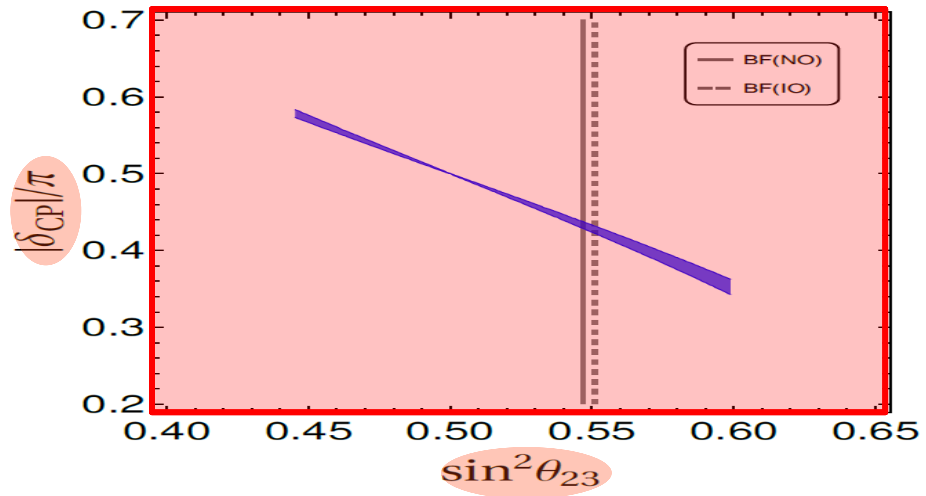
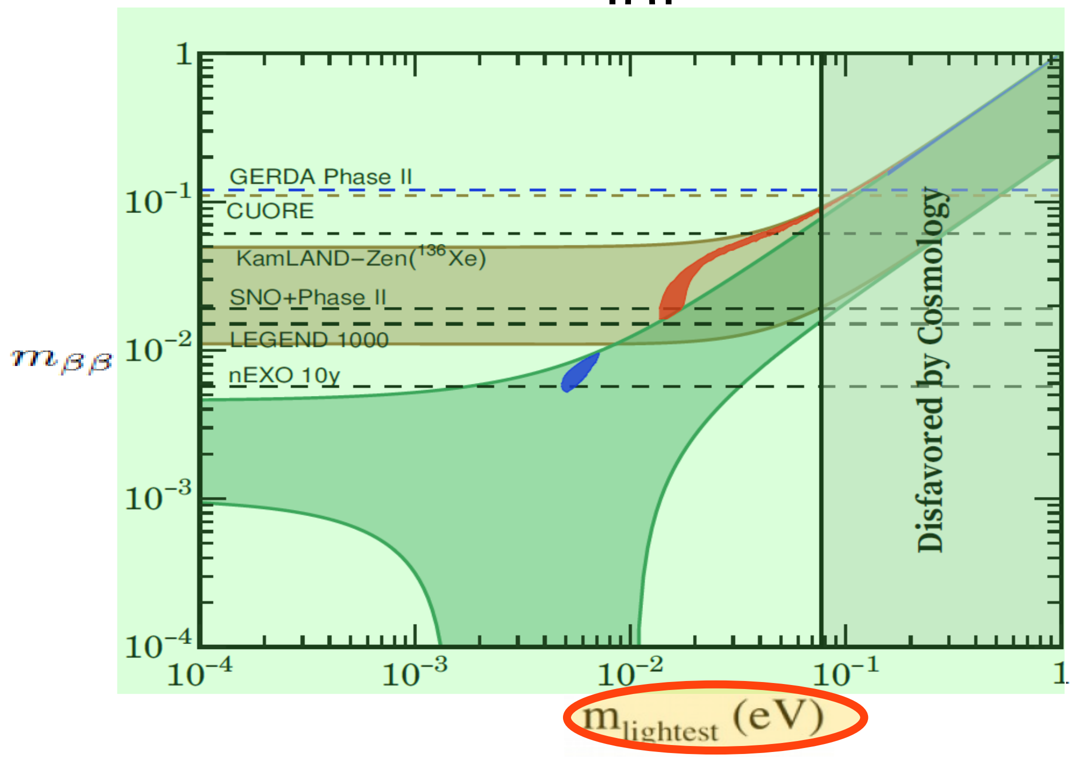


TM1



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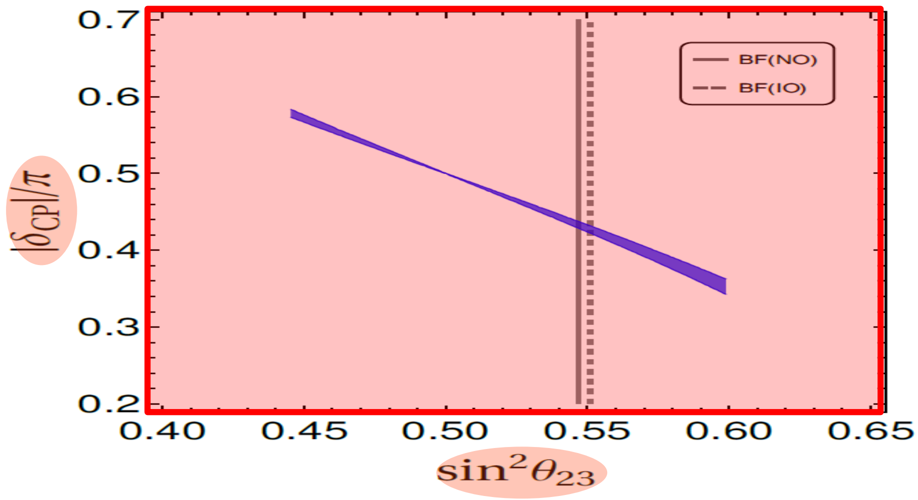

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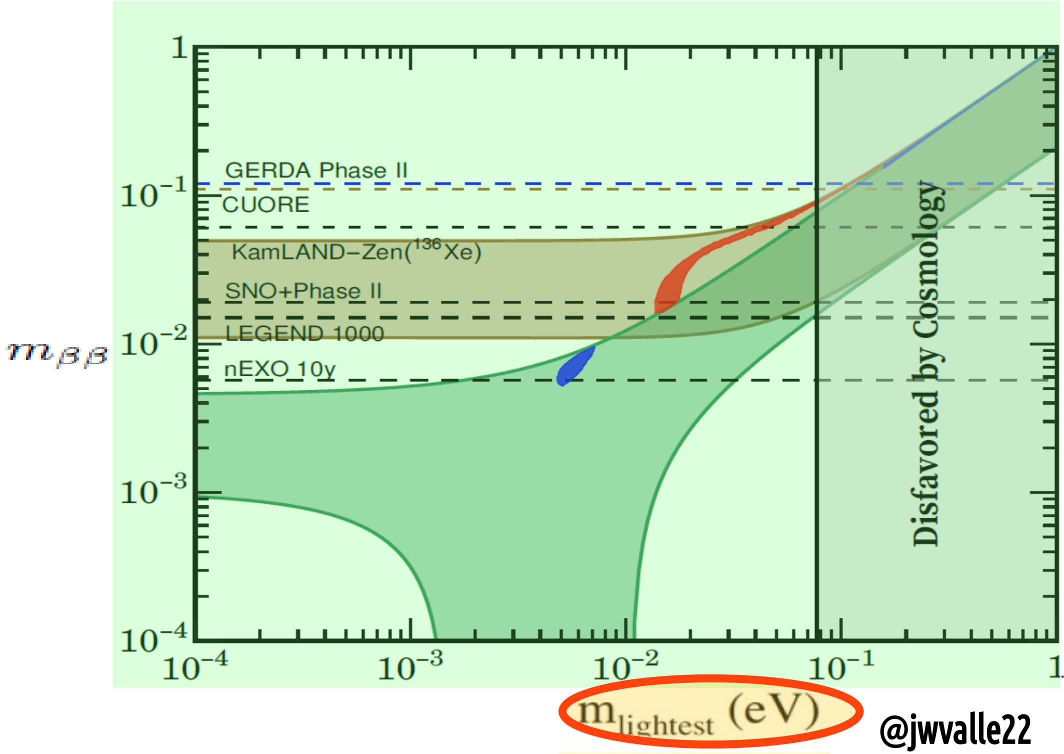


TM2 pattern

Dirac neutrino alternative

Chen et al JHEP01(2016)007

Phys. Rev. D95 (2017) 095030

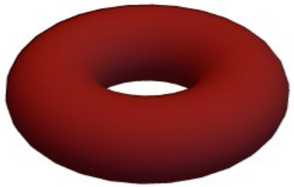
Phys.Lett. B771 (2017) 524

@jwvalle22

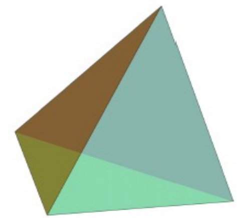
family symmetry from 6D orbifold

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

Phys.Lett.B 801 (2020) 135195
Phys.Rev.D 101 (2020) 11, 116012
Phys.Rev.D 105 (2022) 055030



A4 family symmetry “derived”



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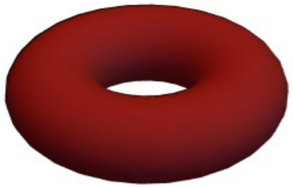

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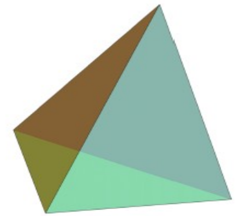
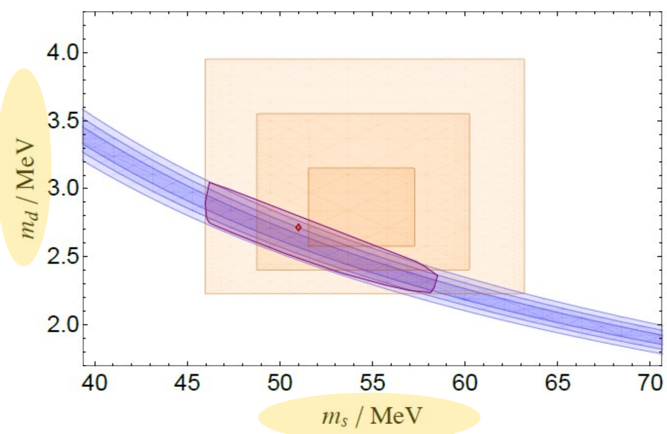


Golden Q-L relation

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



Good global fit of flavor observables

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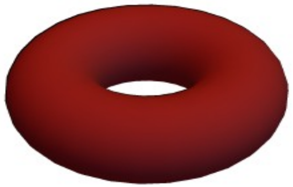
Phys.Lett.B 801 (2020) 135195
Phys.Rev.D 101 (2020) 11, 116012
Phys.Rev.D 105 (2022) 055030



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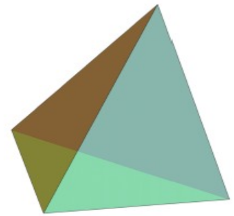

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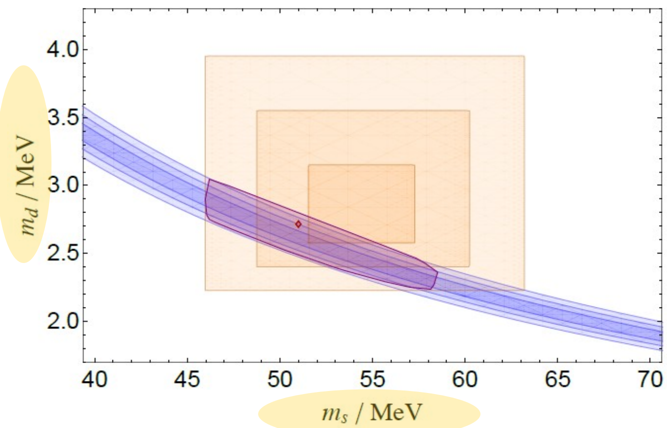
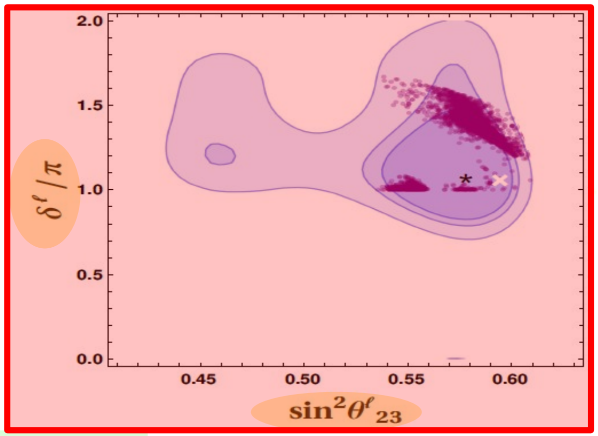
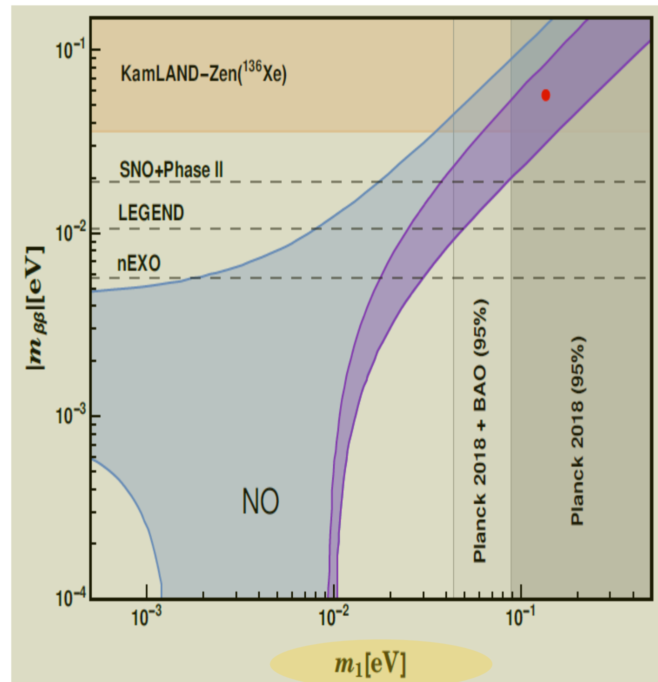


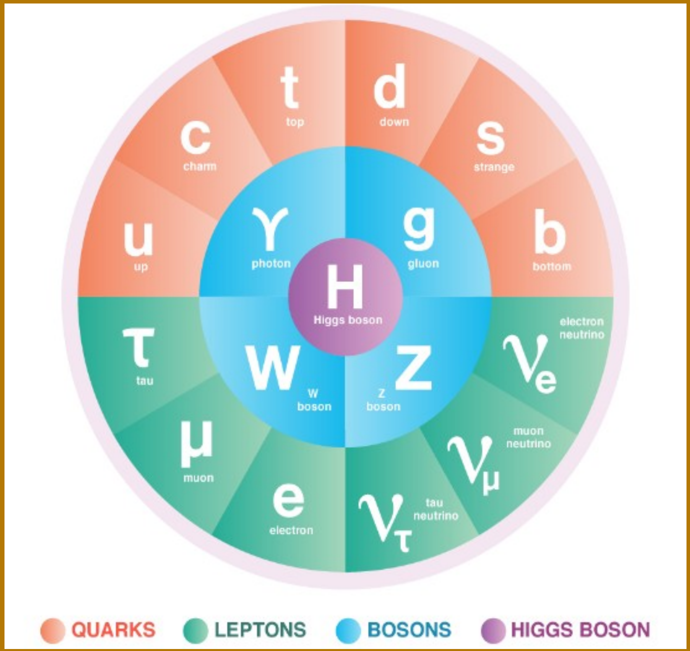




Good global fit of flavor observables

@jwvalle23

HIGGS DISCOVERY NOT THE LAST BRICK TO THE SM



Oscillation discovery brought

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

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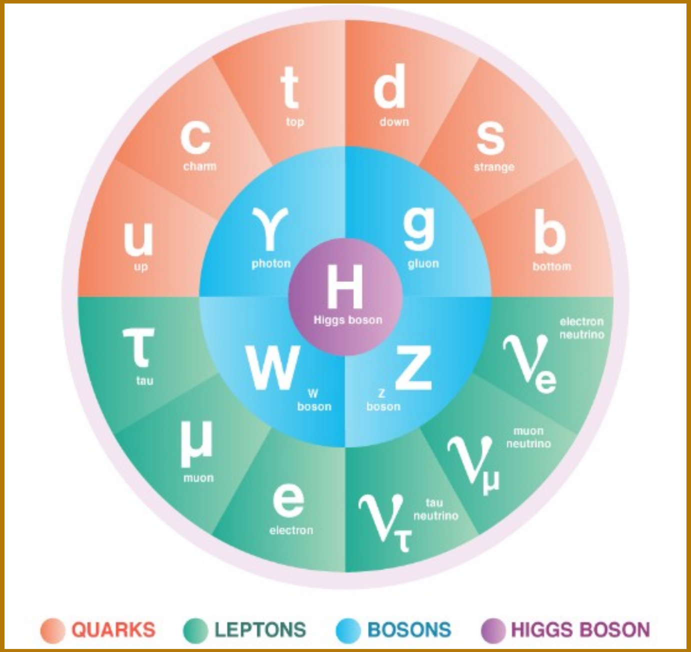

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DM may seed or mediate neutrino mass generation

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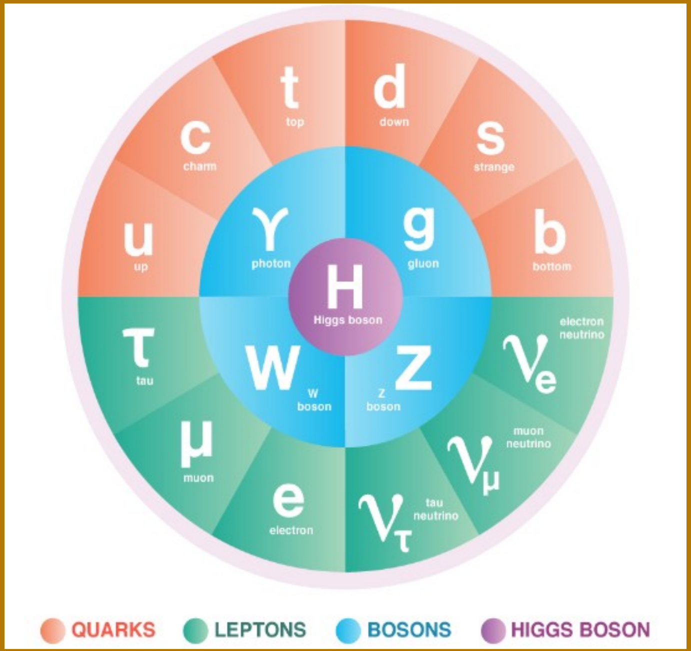

Oscillation discovery brought

precision oscillation program,
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0nuDBD, **CEvNS** ...

neutrinos and **flavor**

neutrinos and strong CP problem

neutrinos and **unification**

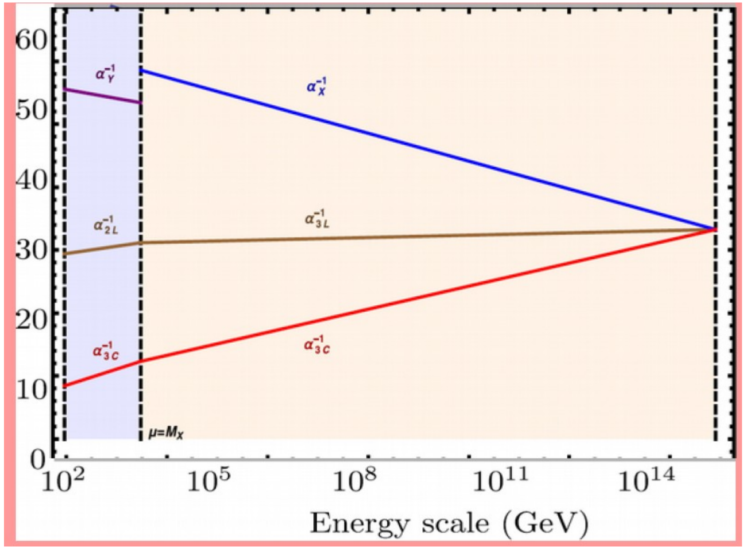
neutrinos and SM anomalies

DM may seed or mediate neutrino mass generation

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

@jwvalle24

Back-ups



neutrino path to unification

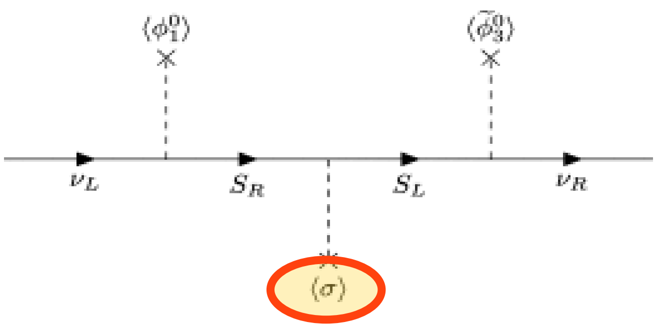
the physics responsible for neutrino masses may also induce gauge coupling unification

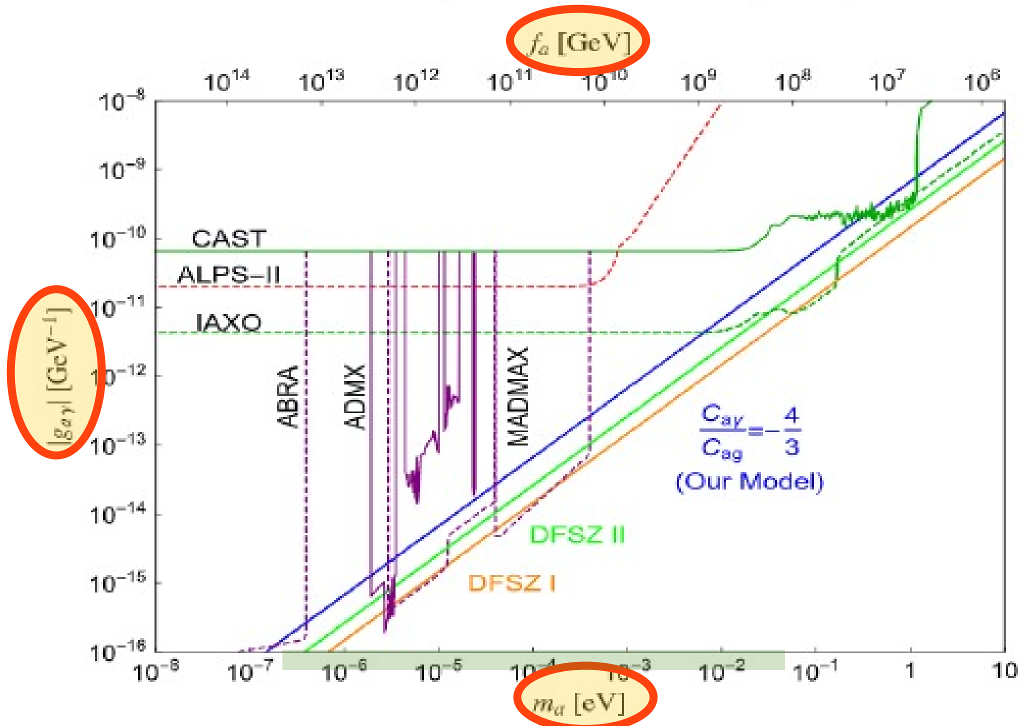
Boucenna et al PRD91, 031702 (2015)

Deppisch et al PLB762 (2016) 432

why 3 families

Physics Letters B 810 (2020) 135829





Dirac type-1 seesaw neutrino mass

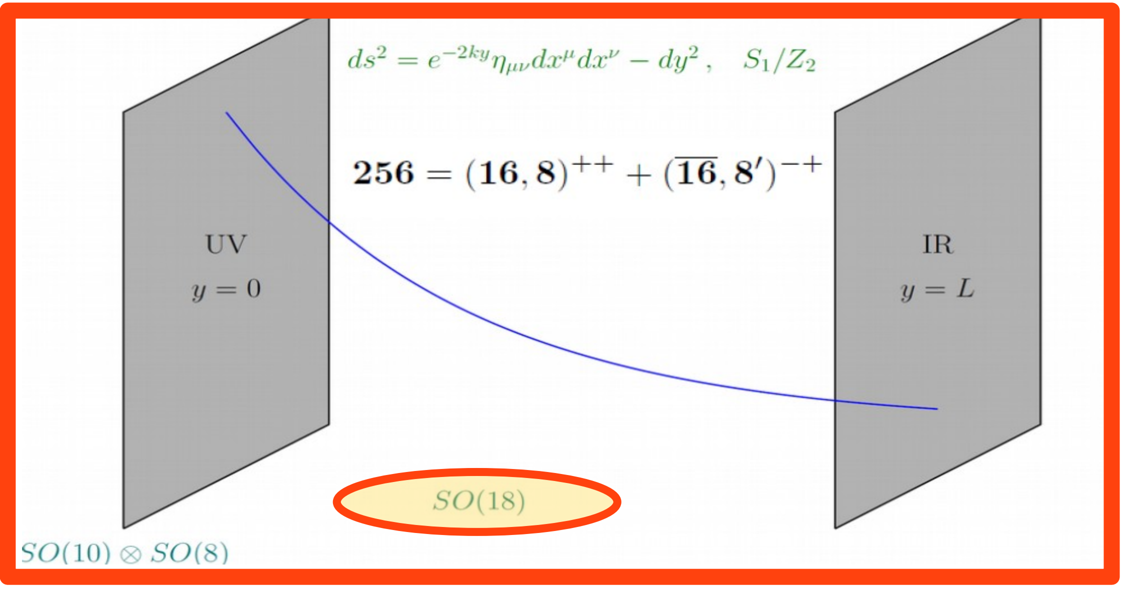
Peccei-Quinn symmetry

tree-level quark FCNC

new path to family unification

inspired by beauty of SO10

Reig Valle Vaquera Wilczek PLB774 (2017) 667



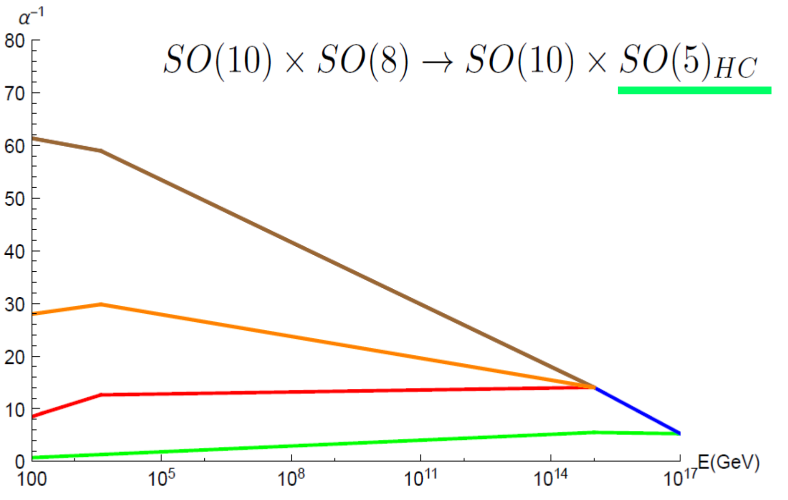
promote M4 to AdS5

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

use orbifold BC to decouple mirrors

unwanted chiral families bound
by new hypercolor force above TeV

new spectroscopy

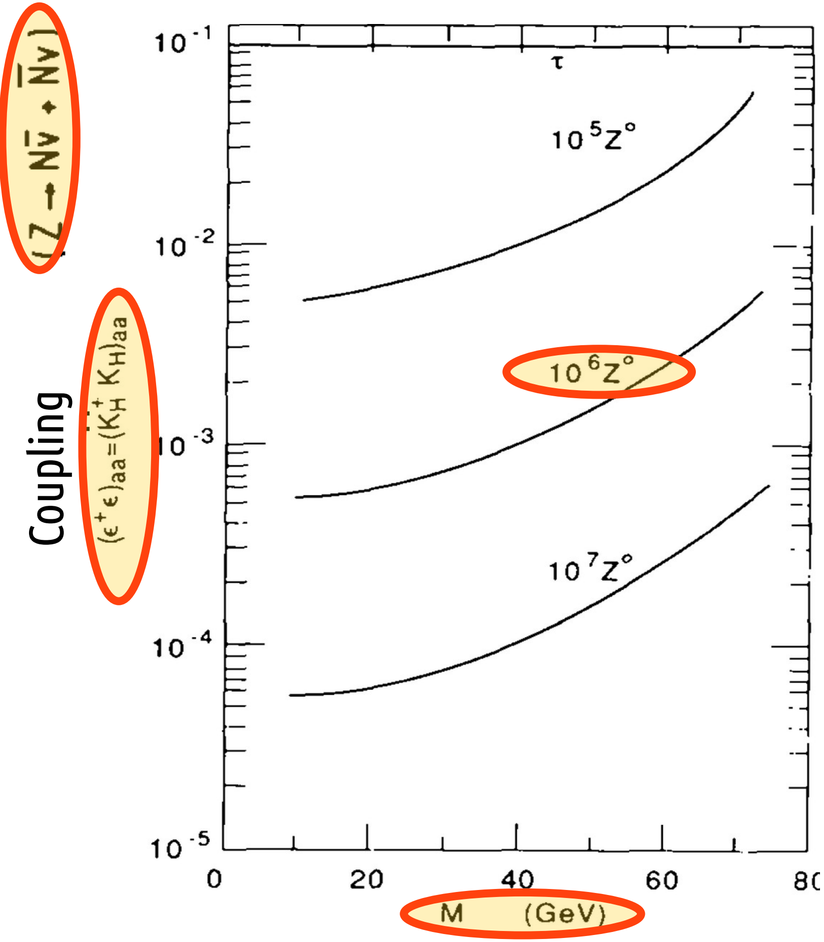


- viable SO3 family symmetry
- golden Q-L mass formula
- PQ symmetry & axion

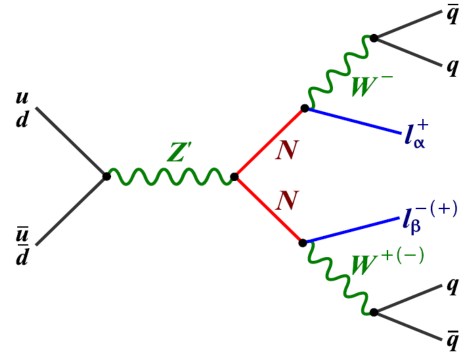
seesaw mediators from gauge portal

Single production via SM Z portal

From Dittmar et al
Nucl.Phys. B332 (1990) 1-19



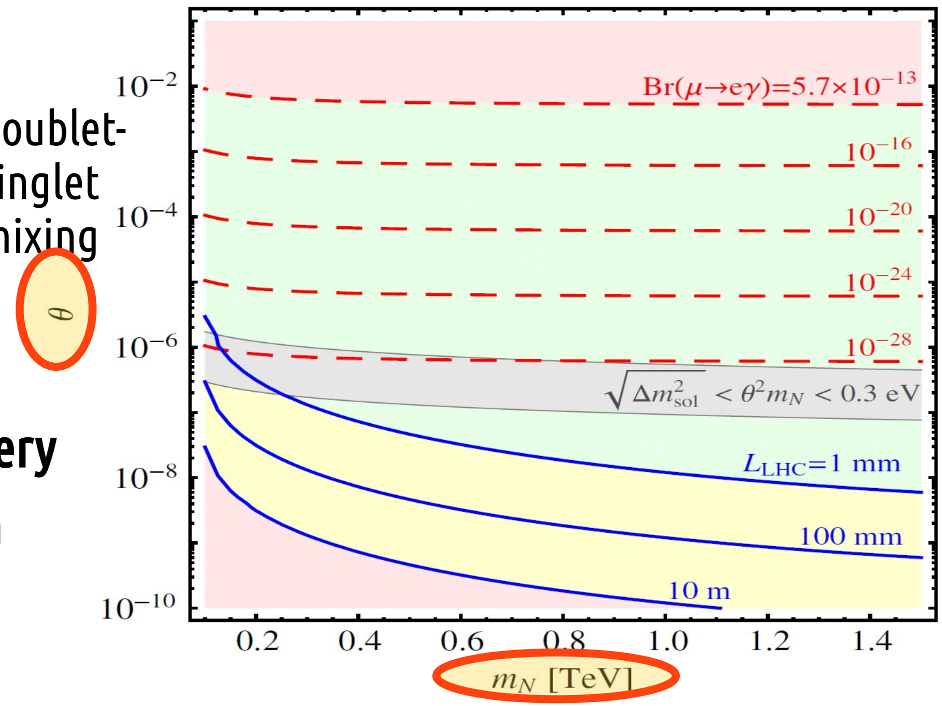
new gauge boson, e.g. Z'...



cLFV at HE

From Phys.Rev. D89 (2014) 051302
L-R symmetry Phys.Rev. D86 (2012) 055006

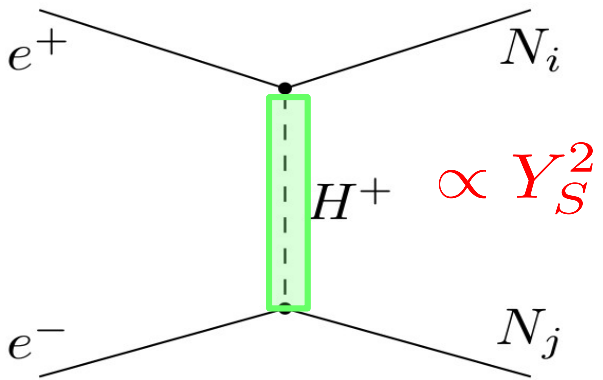
doublet-singlet mixing

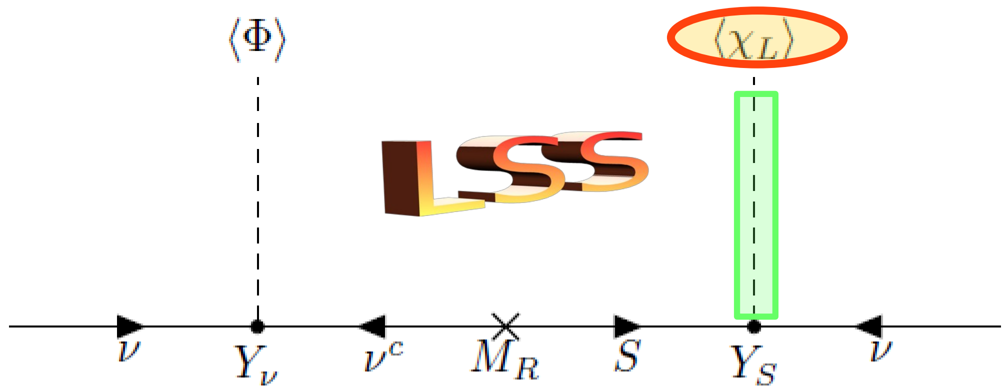


cLFV discovery first at high energies

mediators from higgs portal

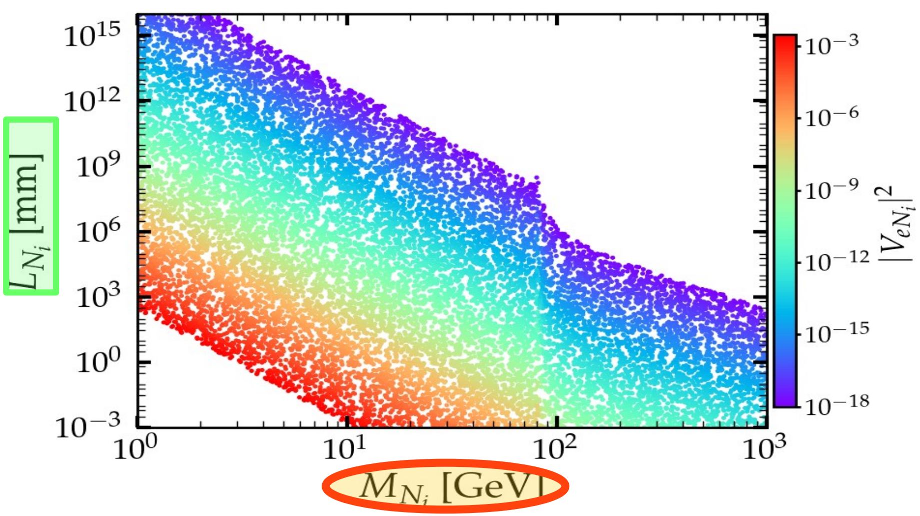
Batra et al, Phys.Lett.B 834 (2022) 137408
JHEP 07 (2023) 221 , 2304.06080

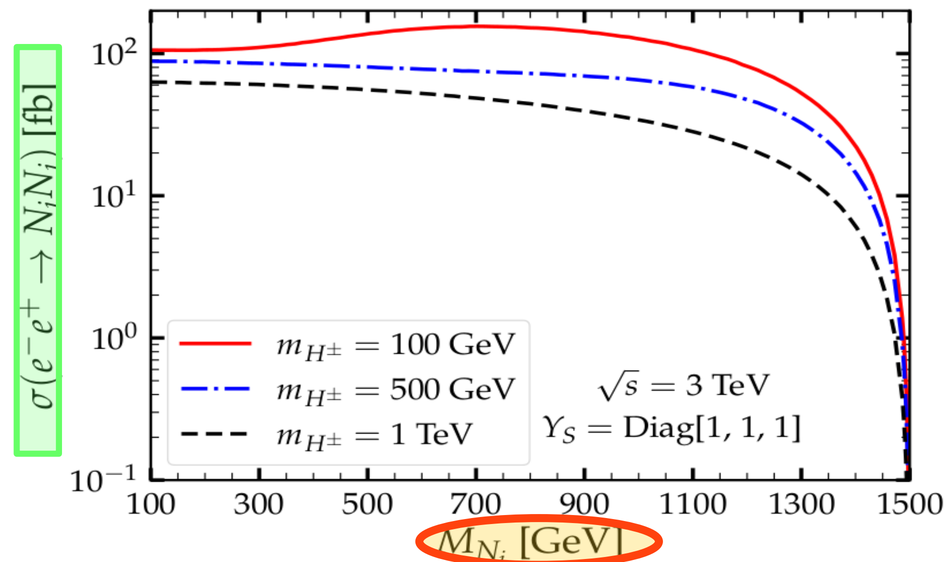




NN production leptophilic Higgs portal

ILC: 1506.07830, **CLIC**: 1812.06018, **CEPC**: 1811.10545
FCC-ee Eur.Phys.J.ST 228 (2019) 2, 261-623





linear seesaw & W mass anomaly

$$m_W^{\rm CDF} = 80.4335 \pm 0.0094 \text{ GeV}$$
$$m_W^{\rm SM} = 80.354 \pm 0.007 \text{ GeV}$$

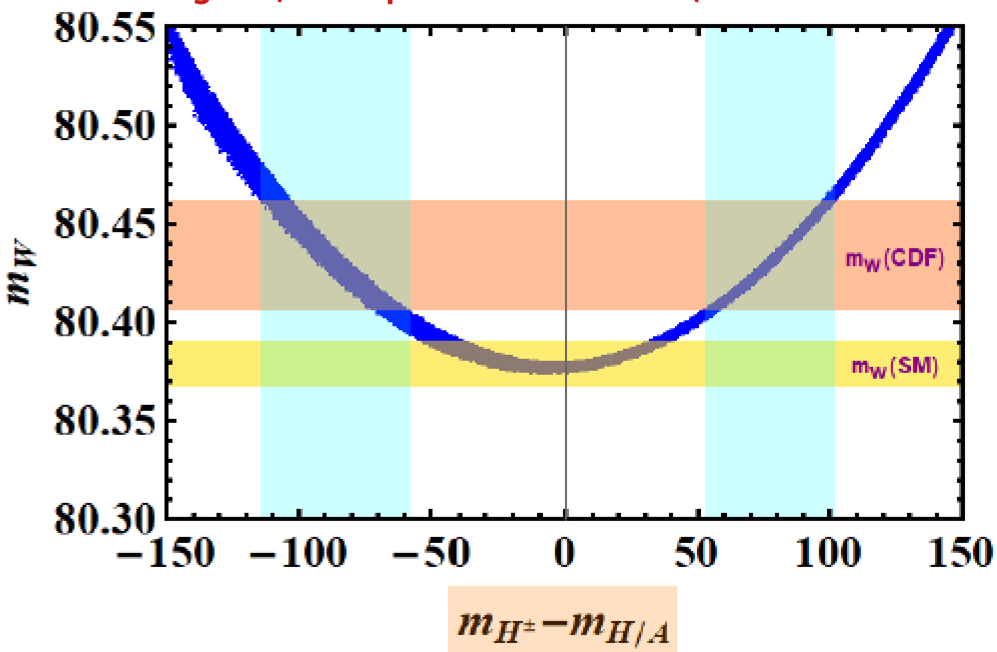
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M_R \\ M_L^T & M_R^T & 0 \end{pmatrix}$$

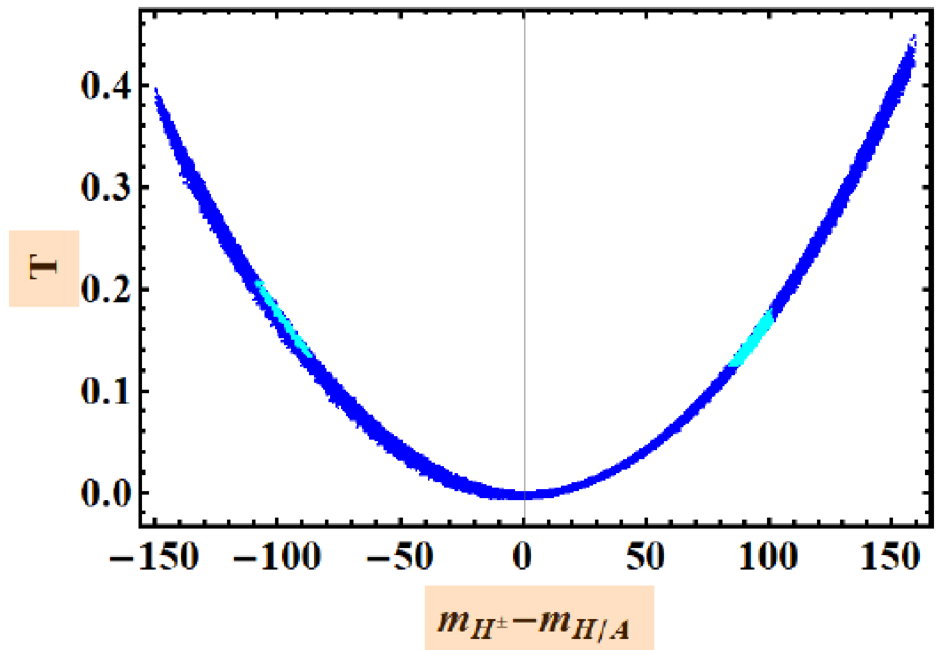
$$m_W^2 = m_W^2\big|_{\rm SM}\left(1 + \frac{s_W^2}{c_W^2 - s_W^2}\,\Delta r\big|_{\rm NP}\right)$$

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

Phys.Lett.B 834 (2022) 137408

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



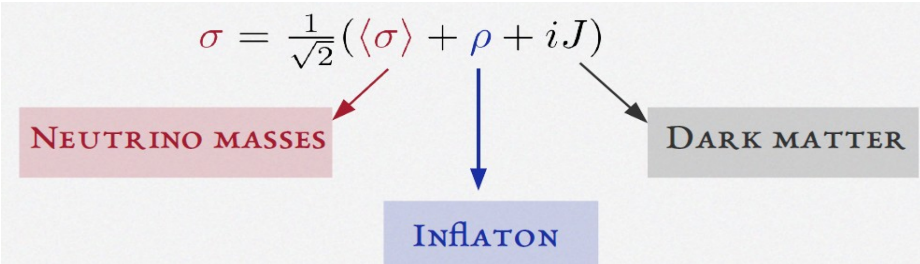


majoron warm dark matter

DM Berezinsky, Valle PLB318 (1993) 360

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

LG Aristizabal et al JCAP 1407 (2014) 052



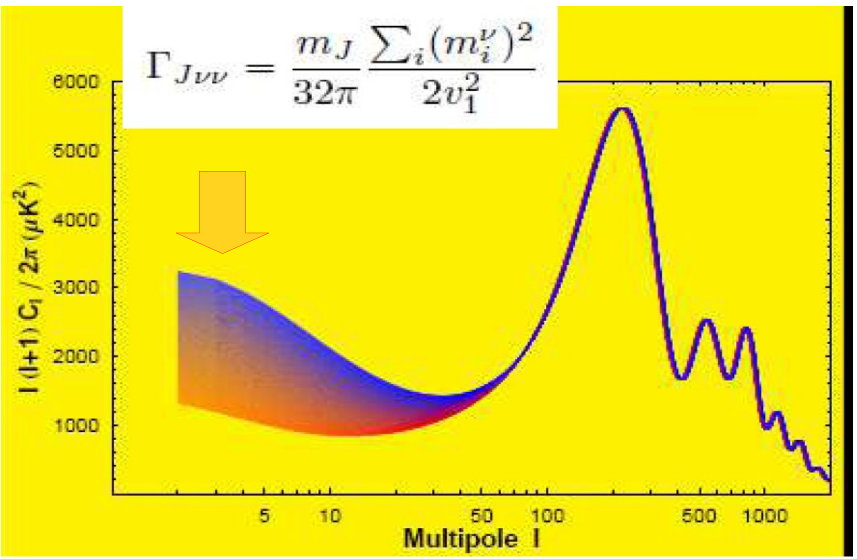
X-rays from DM decay

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

Lattanzi et al PRD88 (2013) 063528

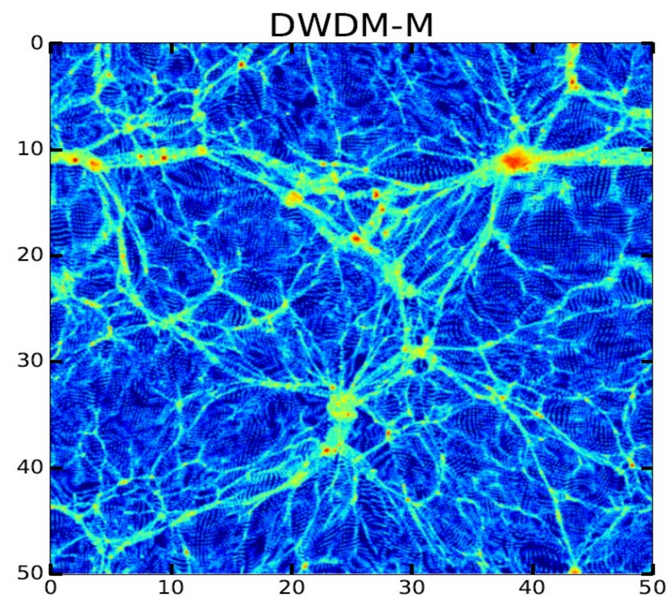
Consistency with CMB

Lattanzi & Valle, PRL99 (2007) 121301



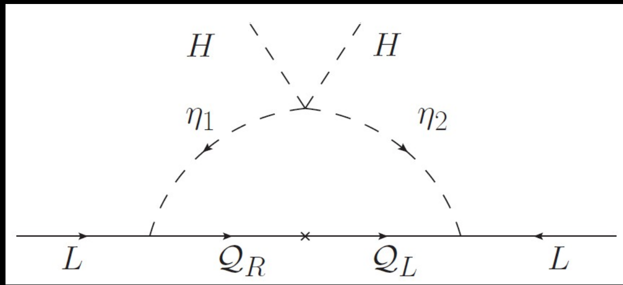
large scale structure

Kuo et al
JCAP 1812 (2018) 026



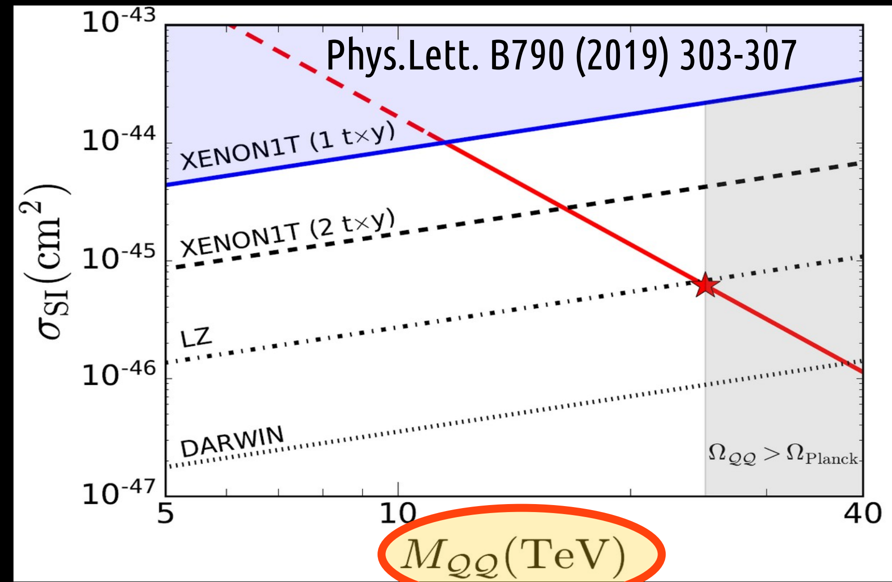
Light majoron CDM Reig, Yamada, JV **JCAP09 (2019) 029**

Bound-state scoto DM



Bound-state dark matter with Majorana neutrinos

M. Reig, D. Restrepo, J.W. F. Valle, O. Zapata
Published in: Phys.Lett.B 790 (2019) 303-307



$$(\mathcal{M}_\nu)_{ij} \sim 0.04\,\text{eV}\left(\frac{M_Q}{12.5\,\text{TeV}}\right)\left(\frac{\lambda_{\eta_1\eta_2 H}v^2}{0.1\,\text{GeV}^2}\right)\left(\frac{15\,\text{TeV}}{\mu_{\eta_1}}\right)^2\left(\frac{h_i y_j}{10^{-6}}\right)$$

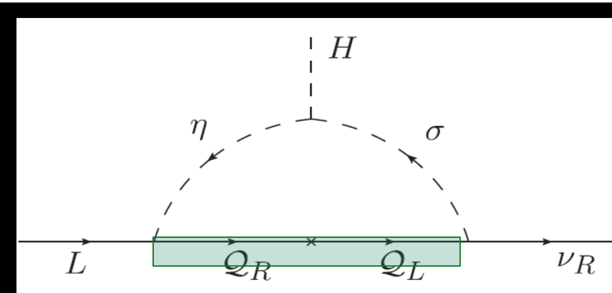
diracness & DM stability

Bonilla et al — Phys.Lett.B 762 (2016) 214 - quarticity

Centelles-Chuliá et al — Phys.Lett.B 767 (2017) 209 – dim5 ops

Leite et al — Phys.Lett.B 807 (2020) 13553 – Phys.Lett.B 817 (2021) 136292

Phys.Rev.D 102 (2020) 1, 015022 - automatic Mp



From Reig et al
Phys.Rev. D97 (2018) 115032