Theory Overview on Neutrino Physics

José W F Valle

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Vniversitat de València

Excelencia Severo Ochoa

The Future of Particle Physics: A Quest for Guiding Principles (1-2 de octubre de 2018)

neutrinos and what comes next in HEP

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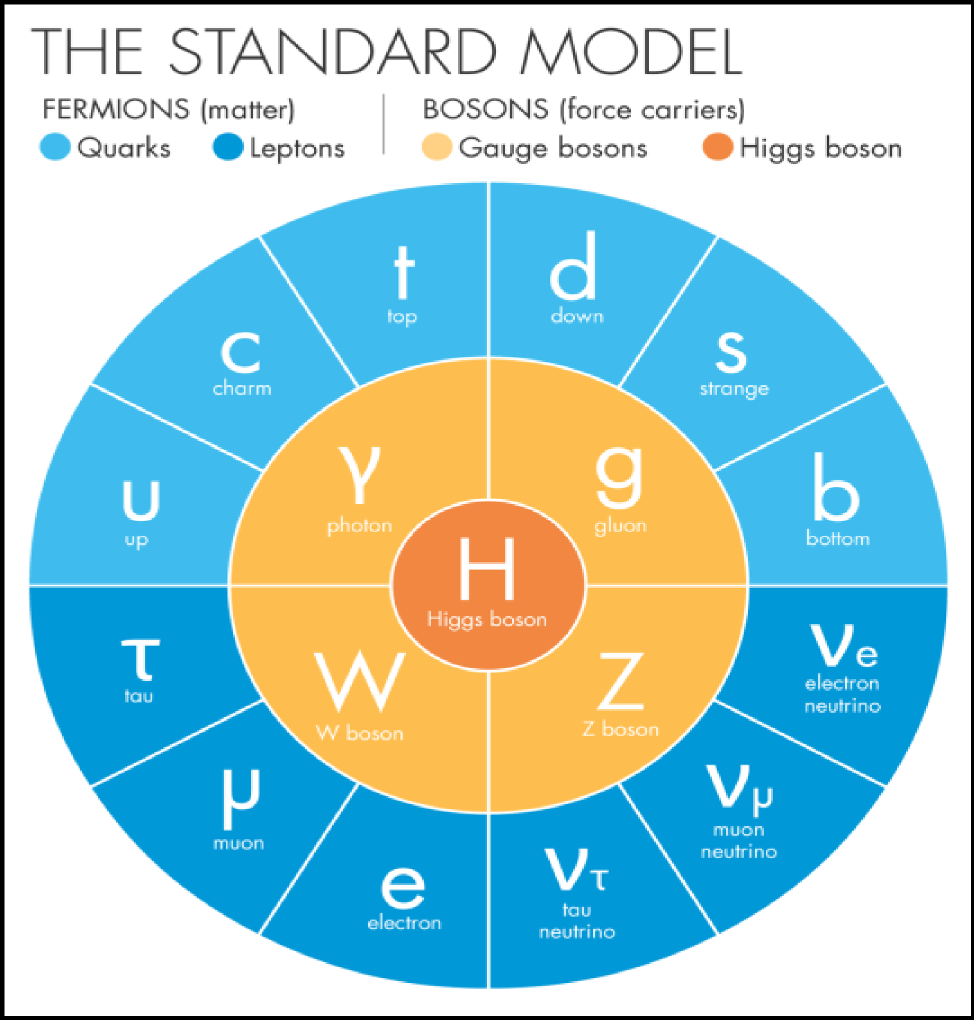
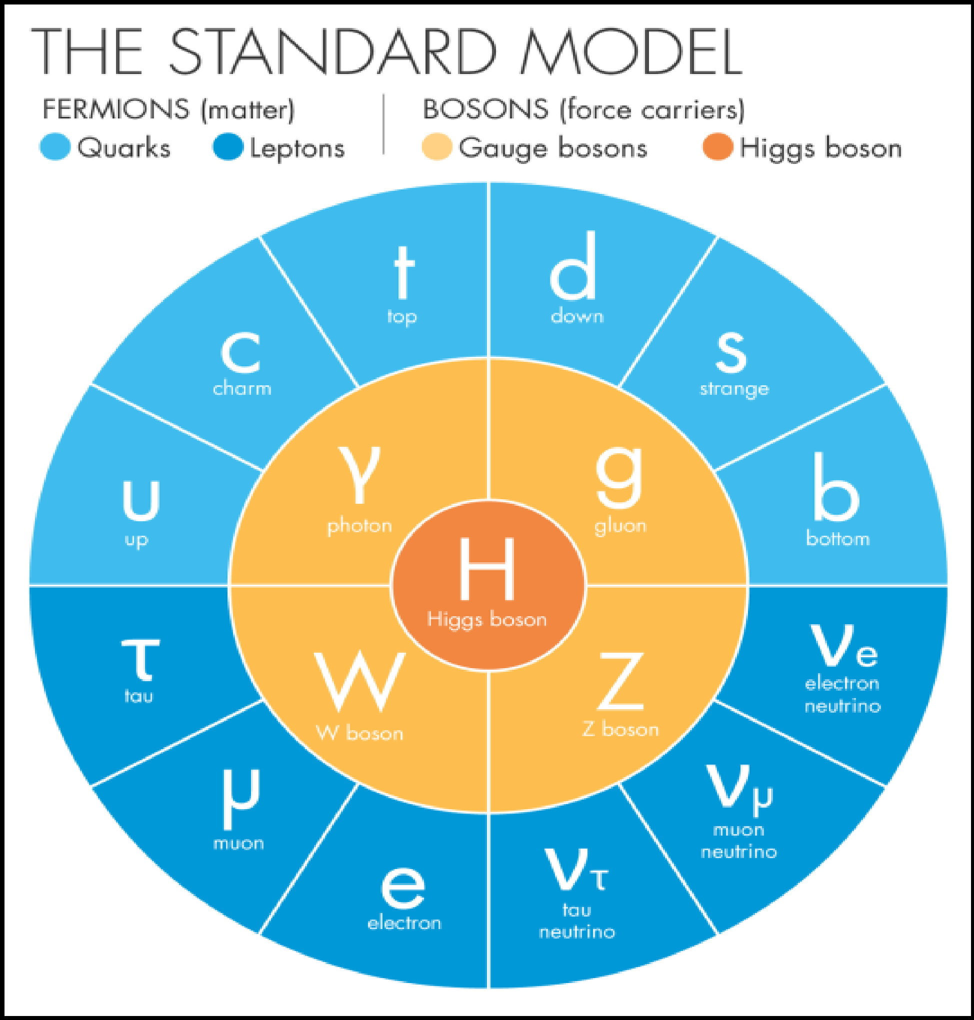

THE STANDARD MODEL
FERMIONS (matter)
Quarks
Leptons
BOSONS (force carriers)
Gauge bosons
Higgs boson
t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
W
W boson
Z
Z boson
τ
tau
νe
electron neutrino
μ
muon
νμ
muon neutrino
e
electron
ντ
tau neutrino

exciting ...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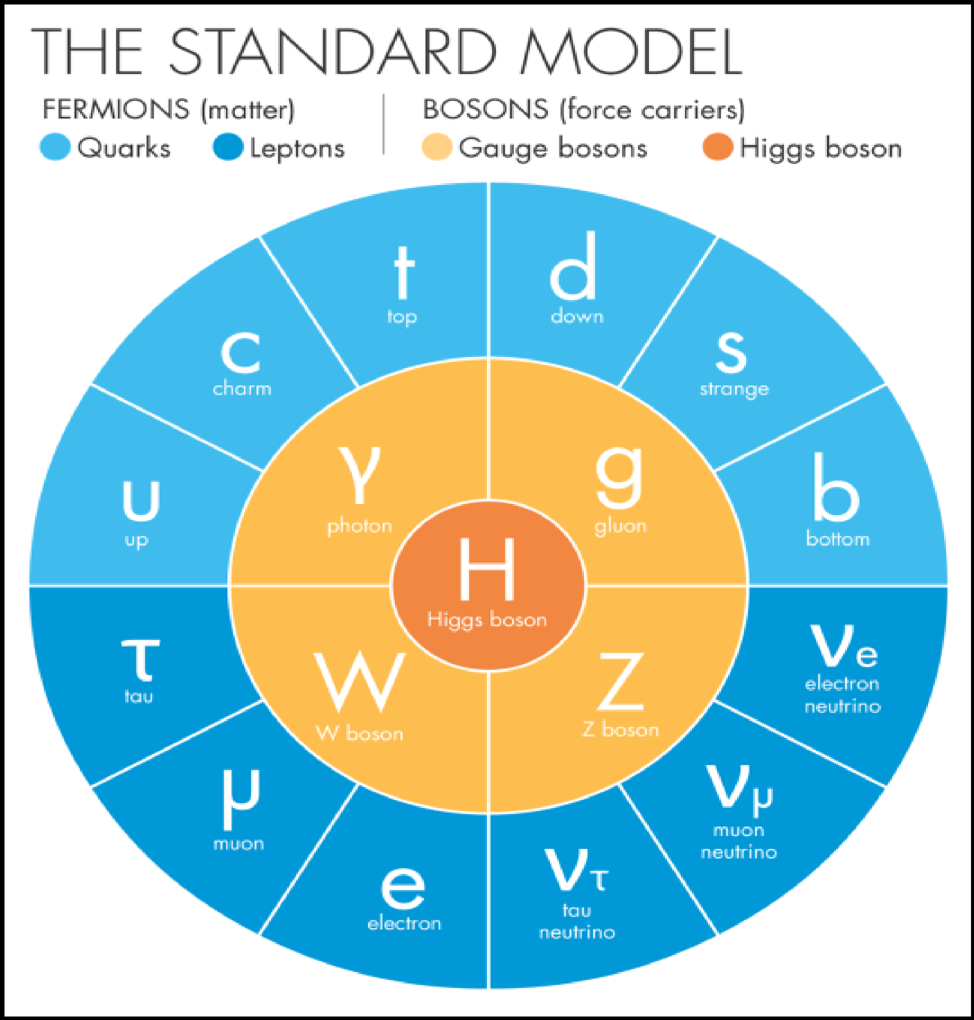
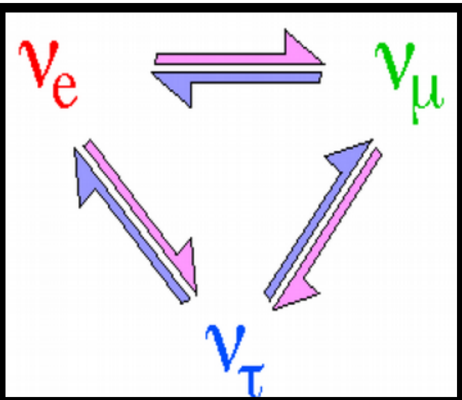
exciting …

Higgs not the last brick !





exciting ...

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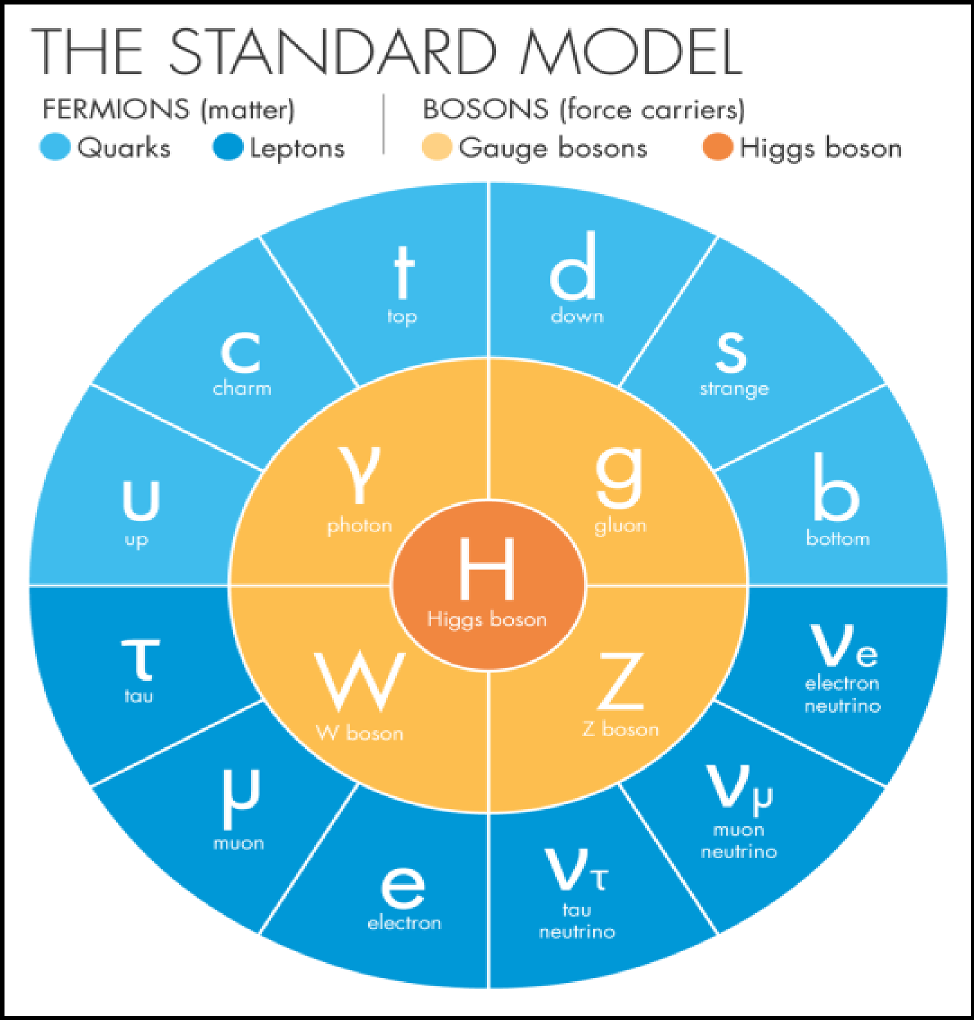
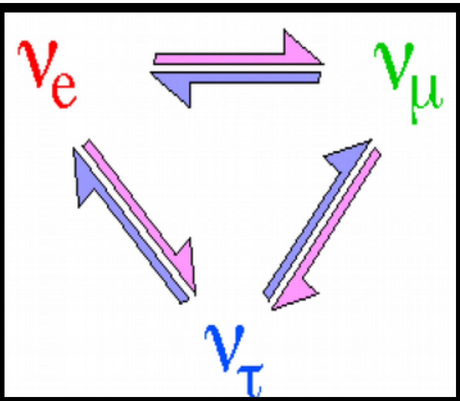
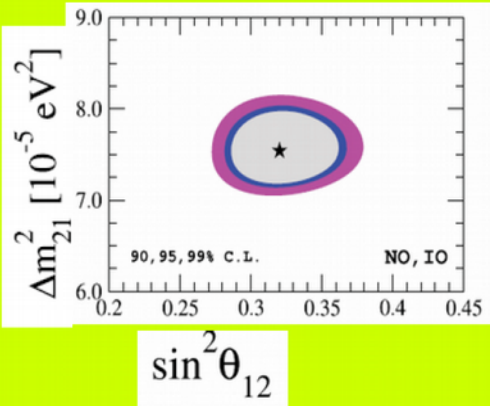
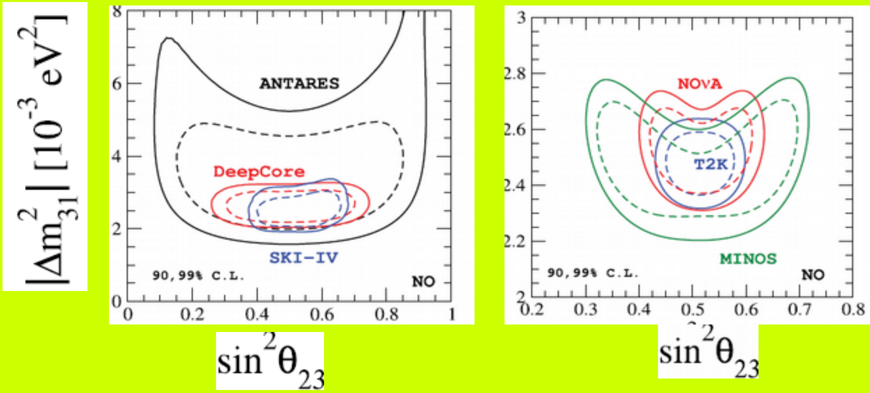




Besides neutrino mass there are many other issues in particle physics & cosmology for which neutrinos may provide key input

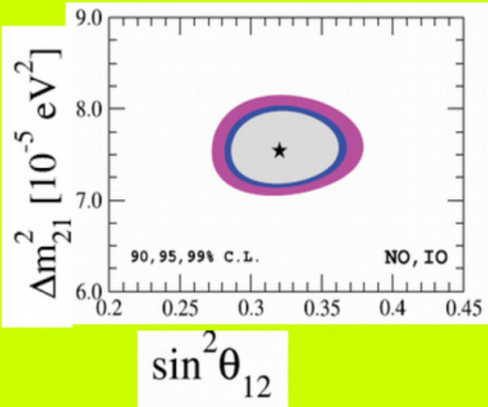
status of neutrino oscillations 2018

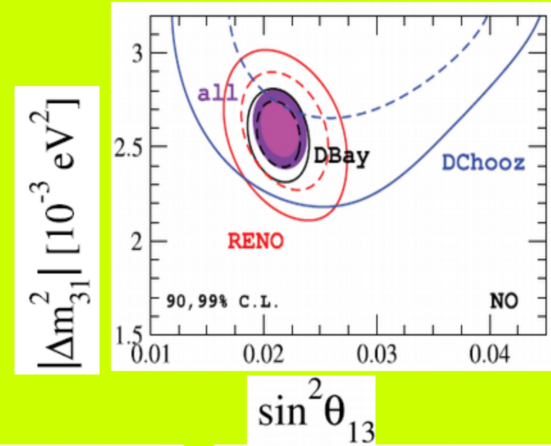


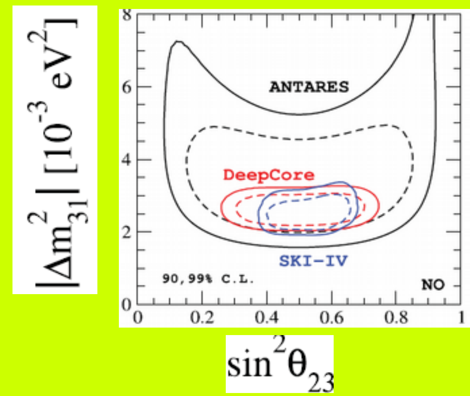


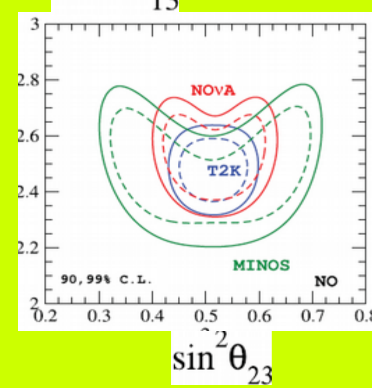
P.F. de Salas et al, PLB782 (2018) 633
https://globalfit.astroparticles.es/

status of neutrino oscillations 2018









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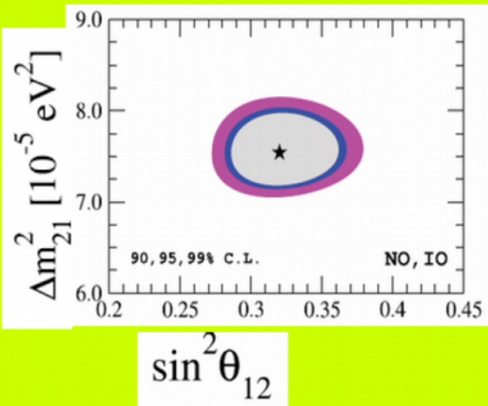
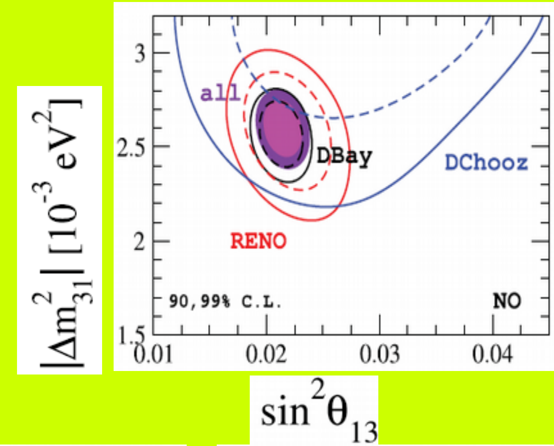
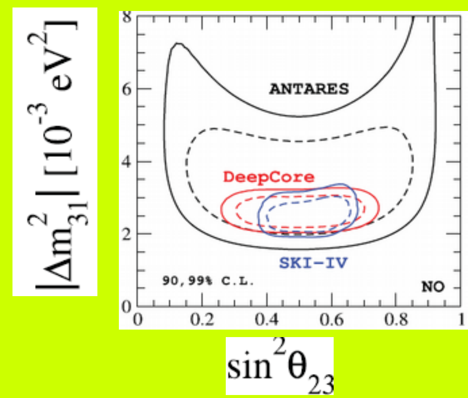
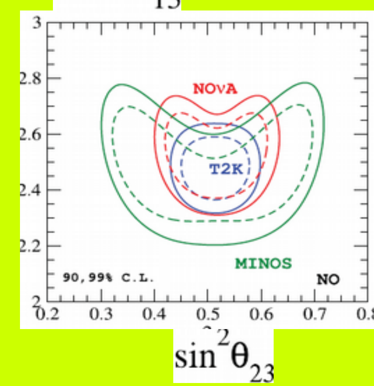
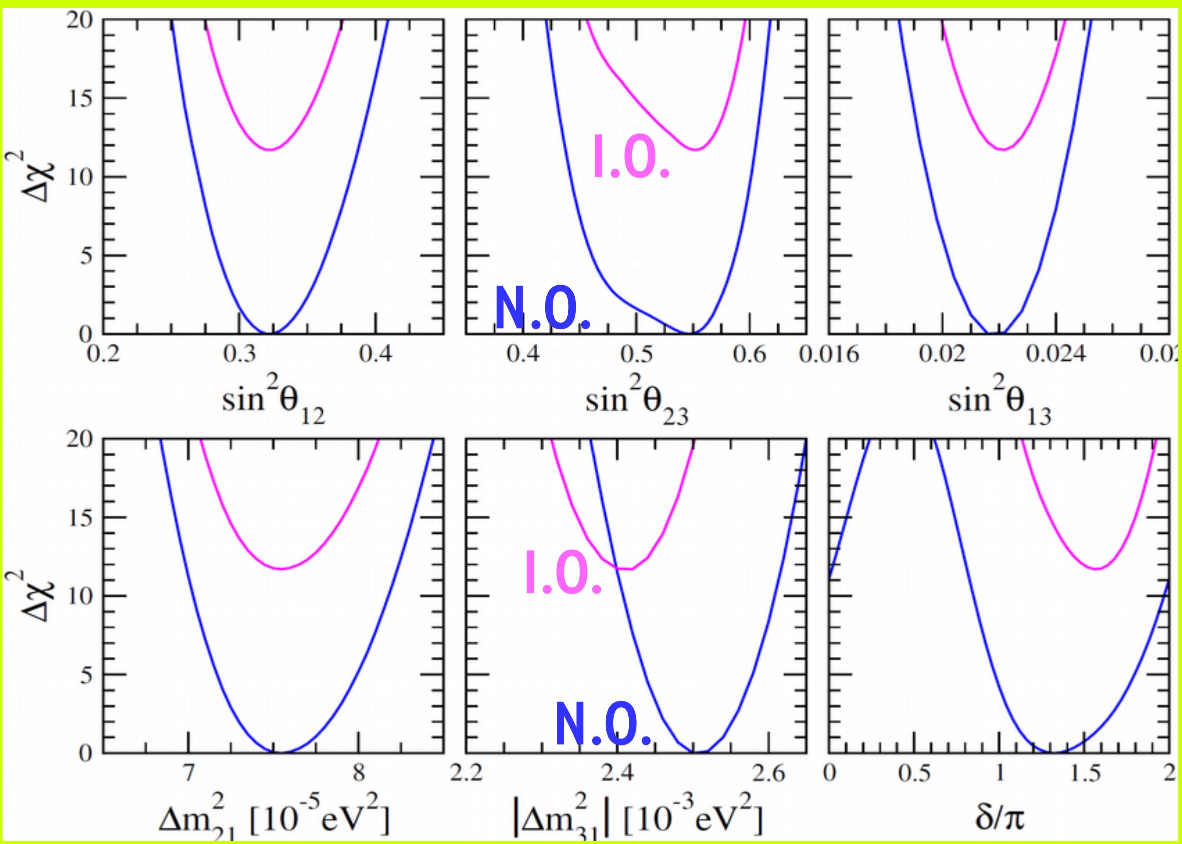
status of neutrino oscillations 2018











P.F. de Salas et al, PLB782 (2018) 633
https://globalfit.astroparticles.es/

Consistent global picture
Good agreement
Good long-term prospects

status of neutrino oscillations 2018

the numbers

precision era requires robustness tests

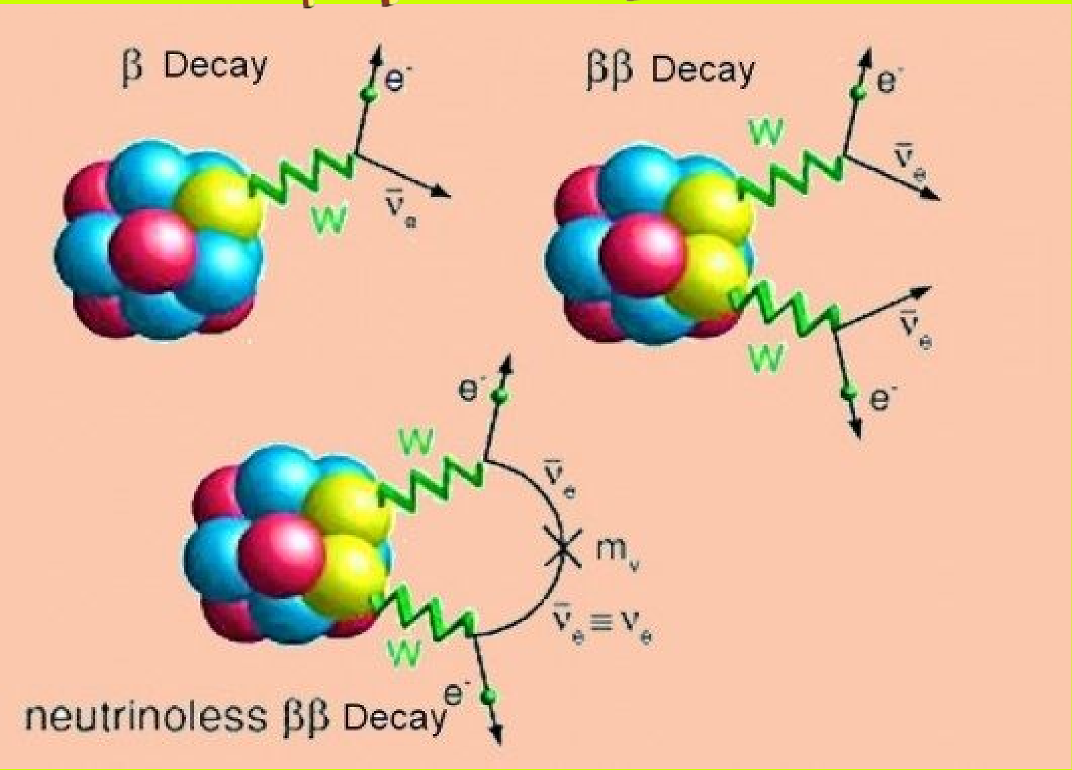
need to go beyond 3-nu paradigm

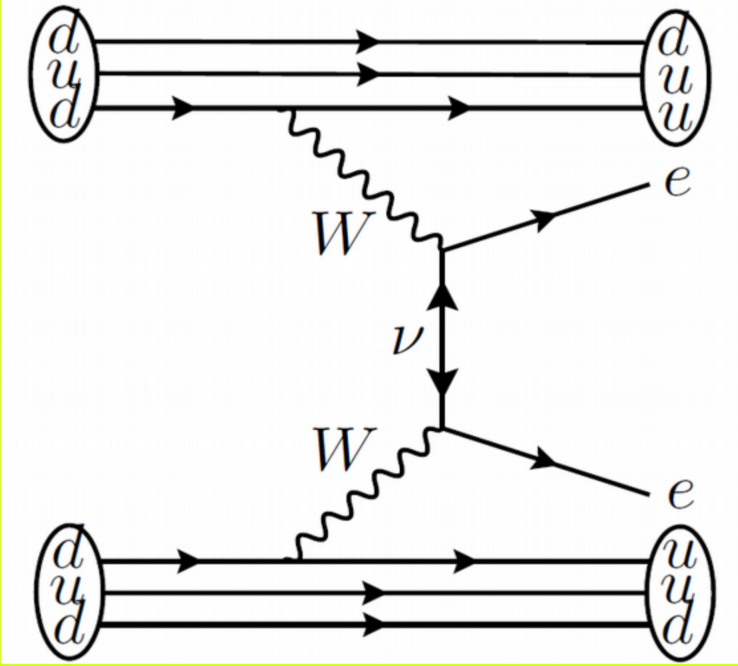
P.F. de Salas et al, PLB782 (2018) 633
https://globalfit.astroparticles.es/

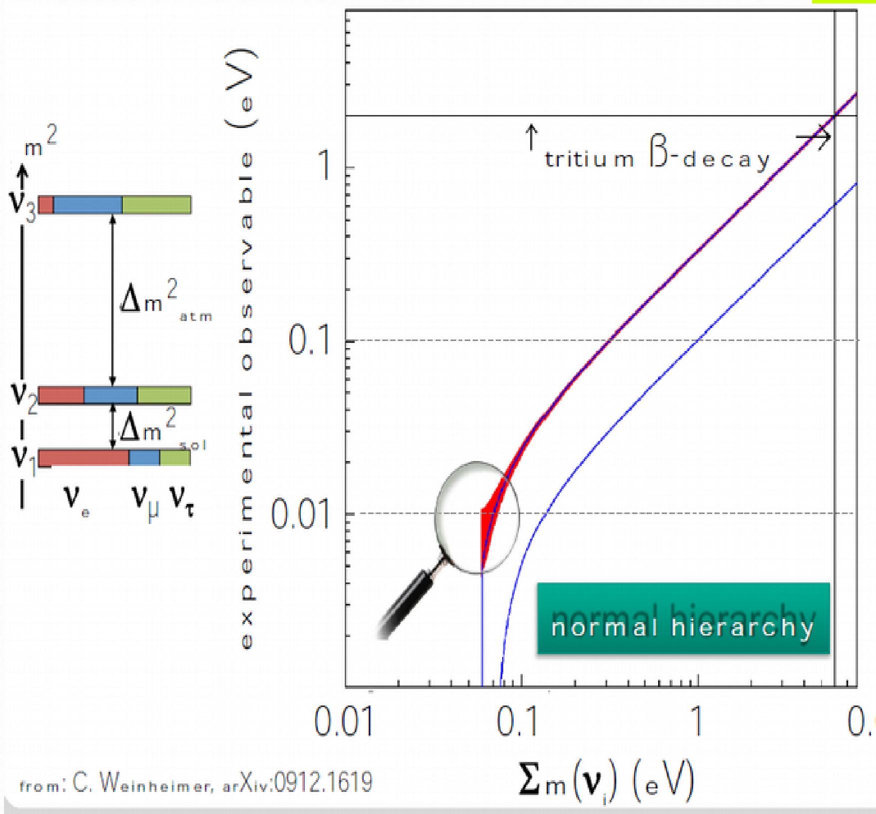
Neutrino oscillation parameters summary determined from this global analysis. The ranges for inverted ordering refer to the local minimum for this neutrino mass ordering.

Parameter	Best fit ± 1σ	2σ range	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.50±0.03	2.44–2.57	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.34–2.47	2.31–2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/°$	$34.5^{+1.2}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.67–5.83	4.45–5.99
$\theta_{23}/°$	$47.7^{+1.2}_{-1.7}$	43.1–49.8	41.8–50.7
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.91–5.84	4.53–5.98
$\theta_{23}/°$	$47.9^{+1.0}_{-1.7}$	44.5–48.9	42.3–50.7
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	2.03–2.34	1.96–2.41
$\theta_{13}/°$	$8.45^{+0.16}_{-0.14}$	8.2–8.8	8.0–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	2.07–2.36	1.99–2.44
$\theta_{13}/°$	$8.53^{+0.14}_{-0.15}$	8.3–8.8	8.1–9.0
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	1.01–1.75	0.87–1.94
$\delta/°$	238^{+38}_{-27}	182–315	157–349
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94
$\delta/°$	281^{+23}_{-27}	229–328	202–349

nuclear physics as probe of neutrino mass scale







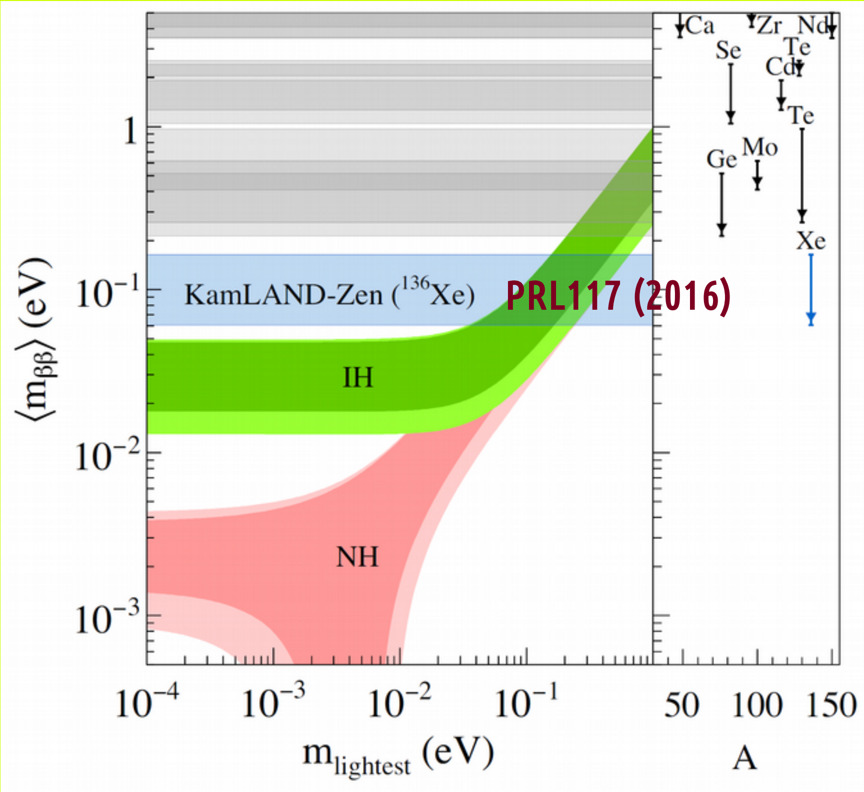
neutrinoless doublebeta decay

historical review
A.S. Barabash arXiv:1104.2714

symmetric parametrization of lepton mixing matrix

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

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



nEXO, **CUORE** , LEGEND (nGERDA/Majorana) ...

neutrinoless doublebeta decay

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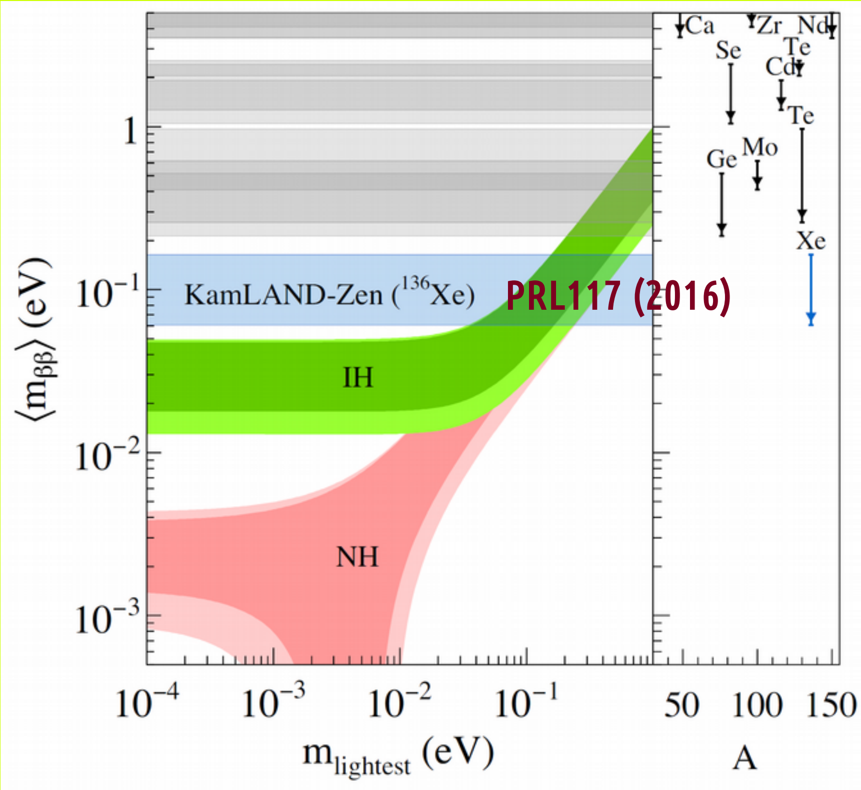

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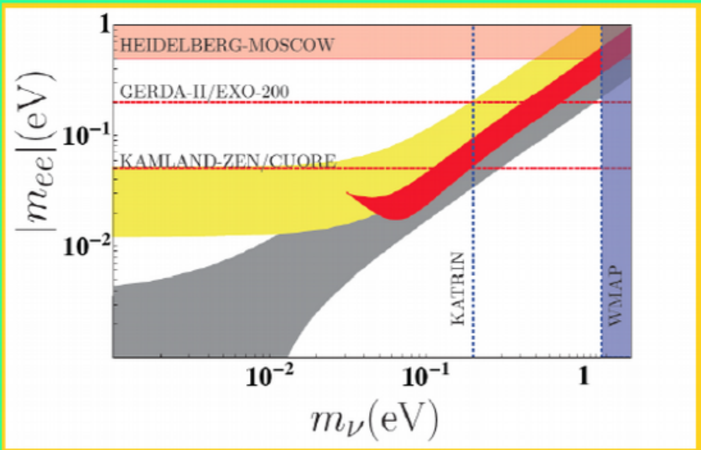
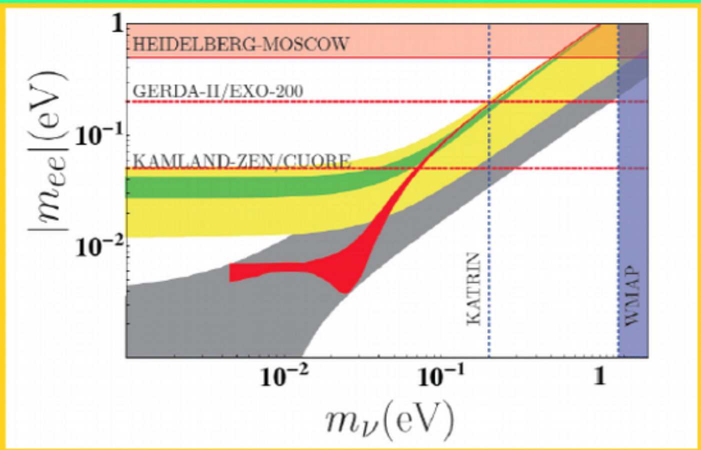
nEXO, **CUORE** , LEGEND (nGERDA/Majorana) ...

lower bounds even for normal ordering

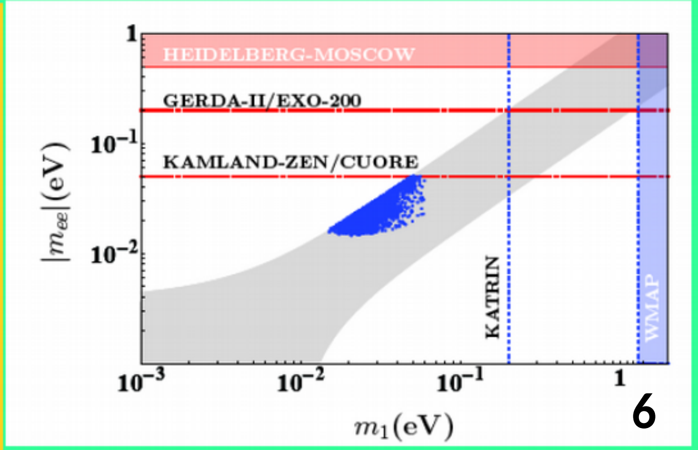
Dorame et al
NPB861 (2012) 259-270



Dorame et al
PhysRevD.86.056001



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

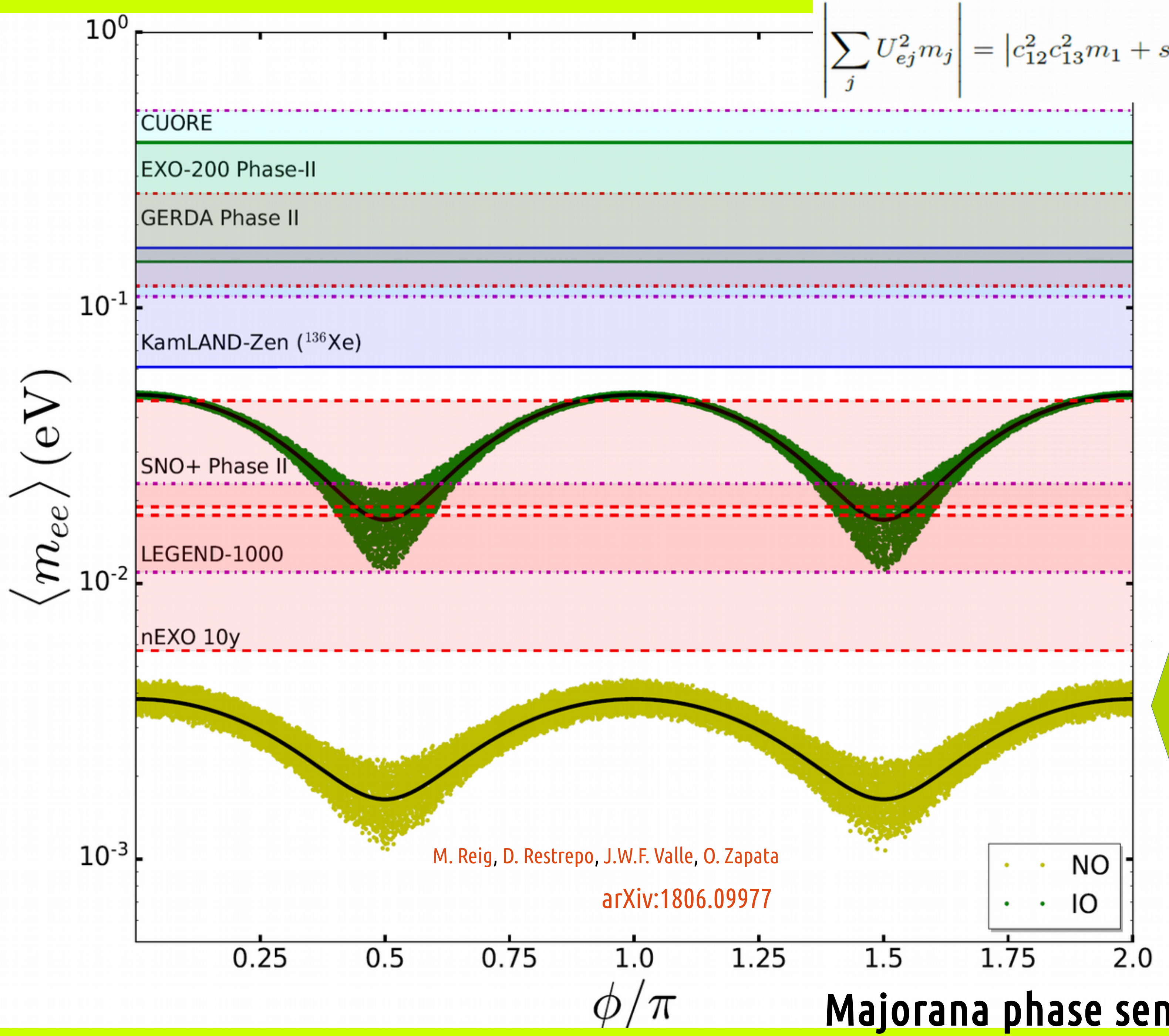


When one neutrino is massless

original symmetric form of lepton mixing matrix

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

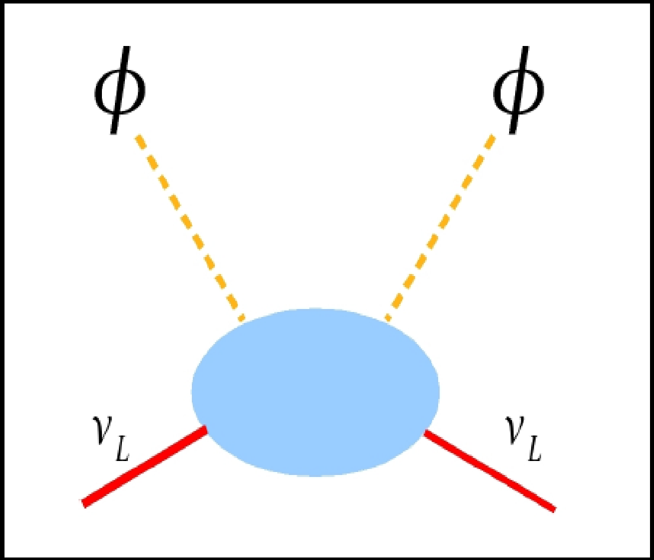
$$\left|\sum_j U_{ej}^2 m_j\right| = \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{2i\phi_{12}} + s_{13}^2 m_3 e^{2i\phi_{13}}\right|$$



lower-bound even for N.O.

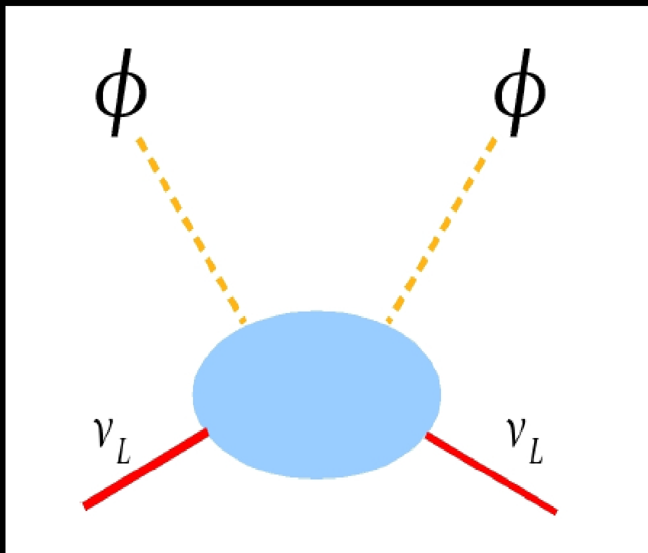
Majorana phase sensitivity ...

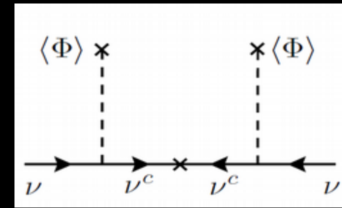
Origin of neutrino mass



coefficient
mechanism
scale
flavor structure

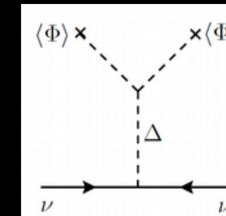
Origin of neutrino mass





TYPE I

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



TYPE II

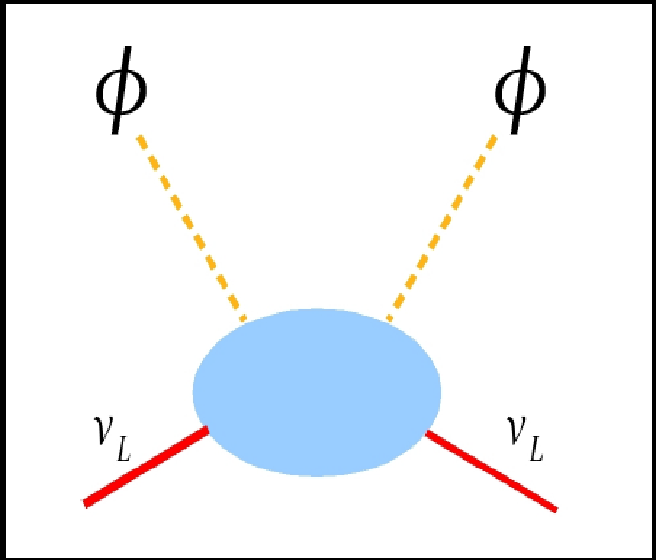
Schechter-Valle 80 & 82

seesaw

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

coefficient
mechanism
scale
flavor structure

Origin of neutrino mass



coefficient
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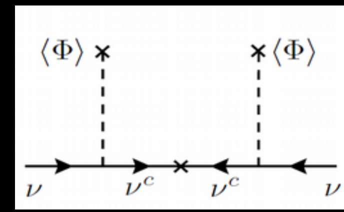

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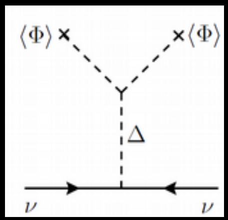


TYPE II

Schechter-Valle 80 & 82

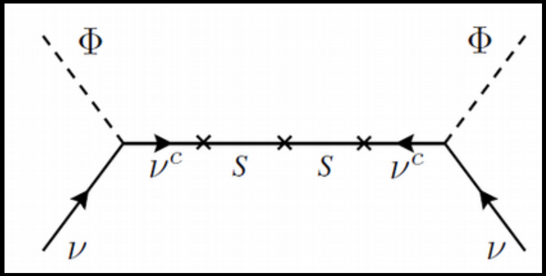
seesaw

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

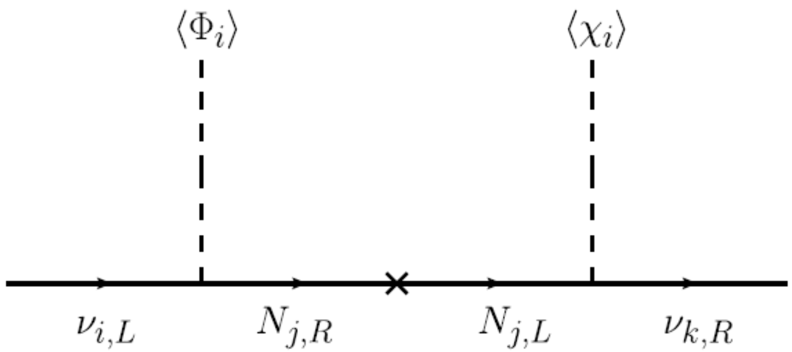
any number of singlet R's w.r.t. L's

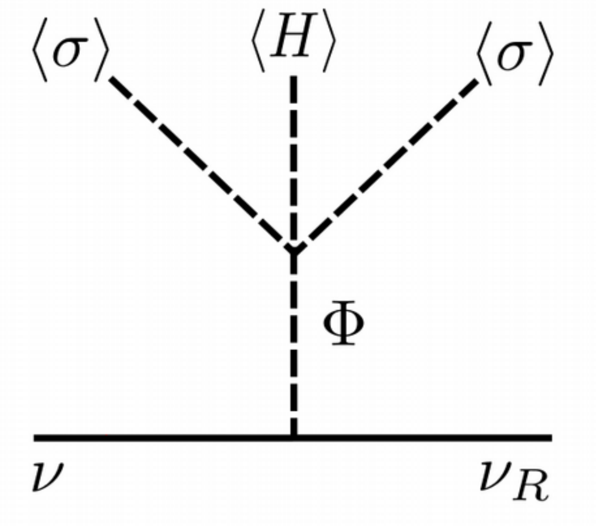
LOW-SCALE SEESAW

Mohapatra-Valle 86
Akhmedov et al PRD53 (1996) 2752
Malinsky et al PRL95(2005)161801
Bazzocchi et al, PRD81 (2010) 051701



Seesawing a la Dirac





type1

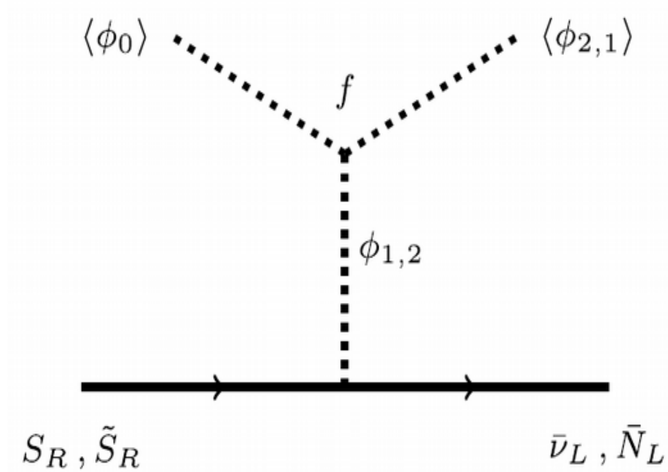
Phys.Lett. B761 (2016) 431-436

Phys.Lett. B767 (2017) 209-213

type2

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



symmetry protects small neutrino mass

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

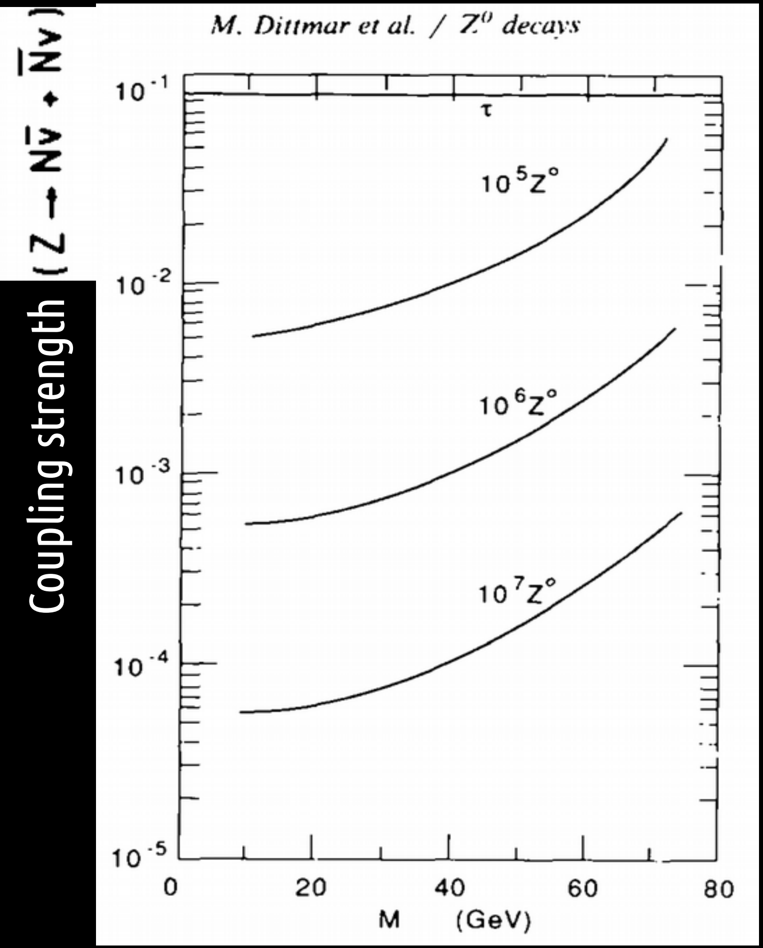
theories of neutrino mass

theories of neutrino mass

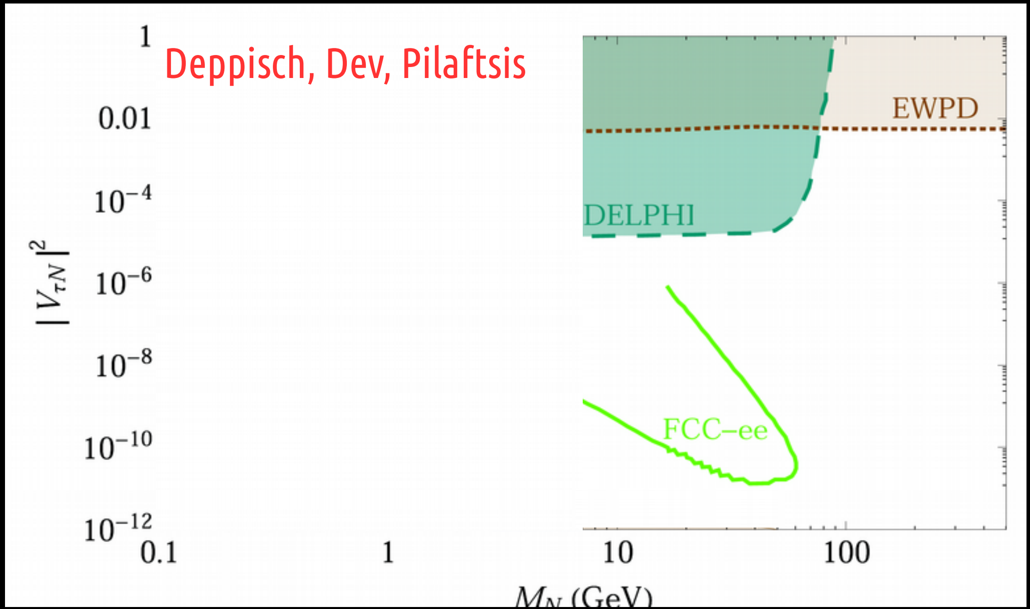
probe neutrino messengers with Displaced Vertices

re-measure neutrino mixing angles @ colliders

Pre-LEP days Dittmar et al Nuclear Physics B332 (1990) 1-19



Limits on coupling strength parameter that can be reached for different number of Zs plotted as a function of the NHL mass. Only leptonic final states included. This is for the tau type NHL neglecting family mixing. The only relevant constraint in this case comes from weak universality



Pre-LEP days

Dittmar et al Nuclear Physics B332 (1990) 1-19

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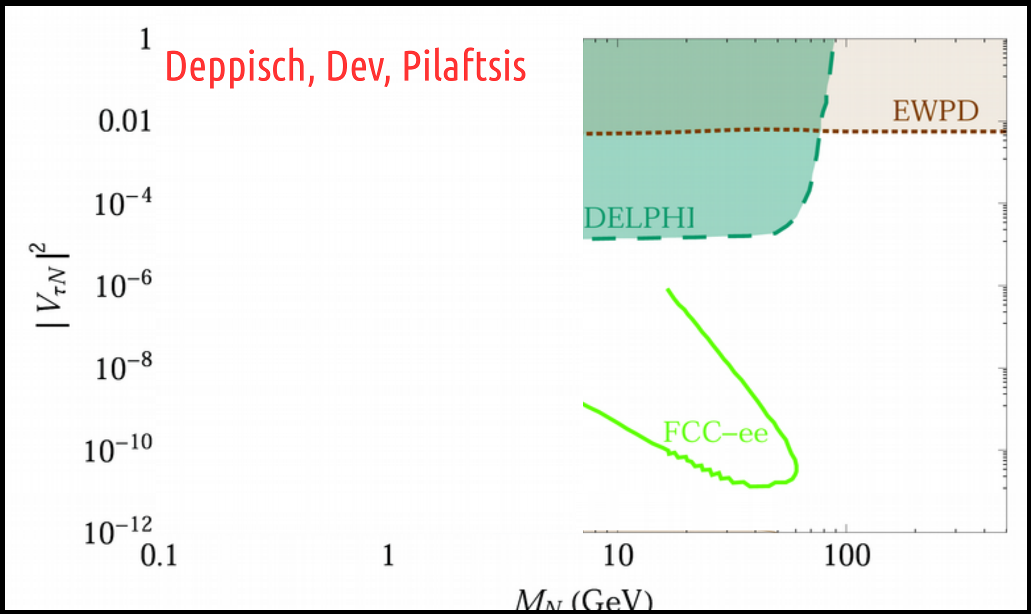
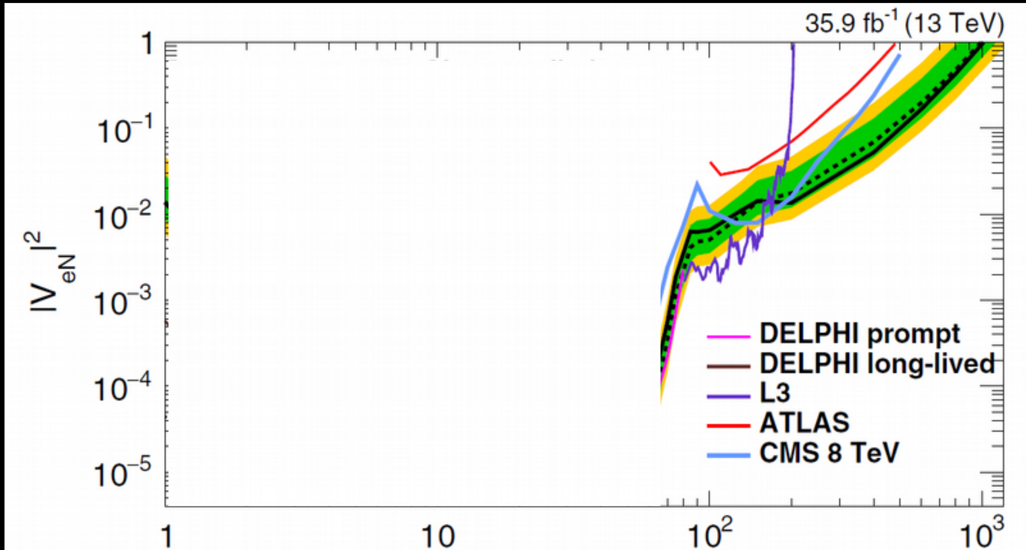
from LEP to LHC





PHYSICAL REVIEW LETTERS **120**, 221801 (2018)

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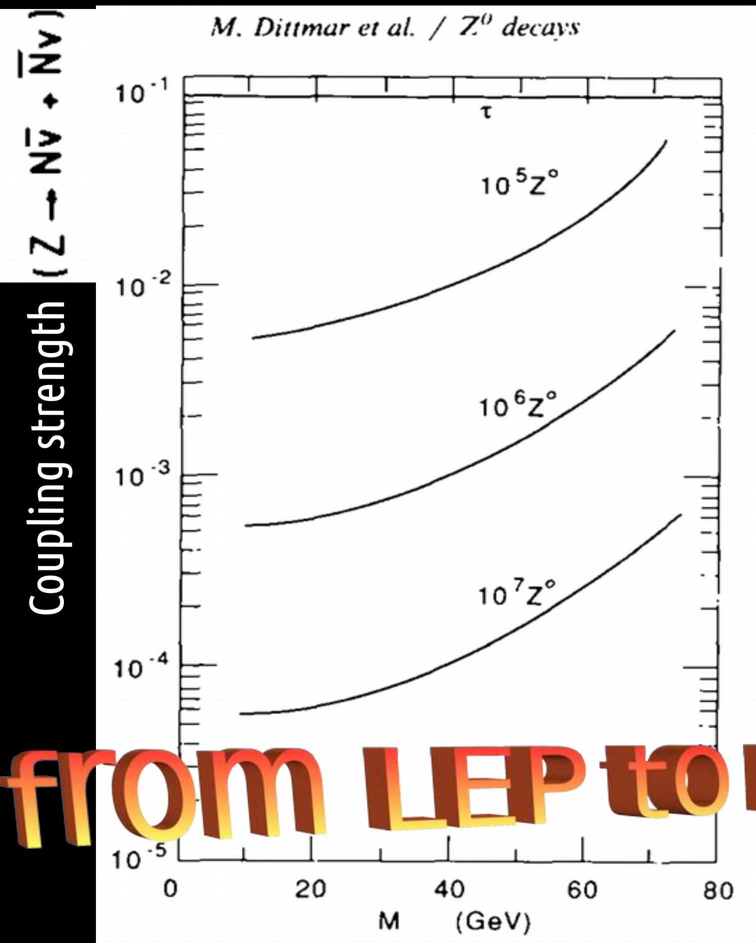
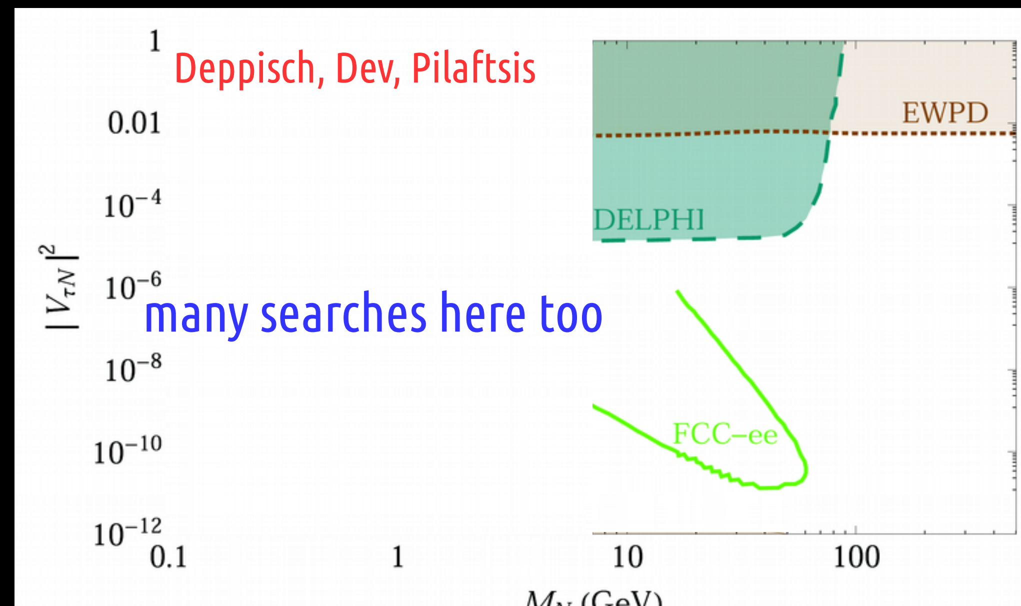
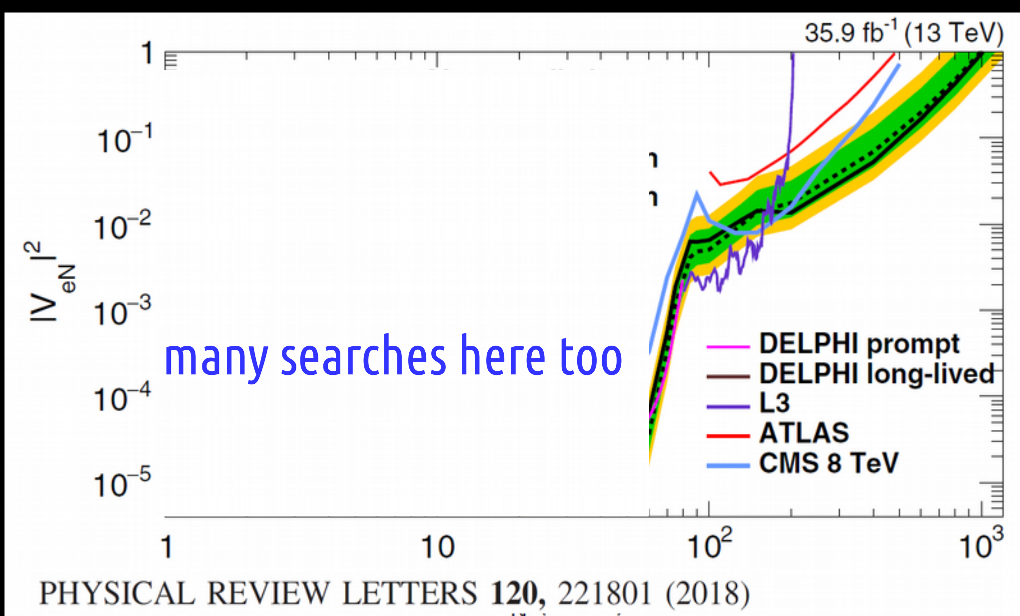
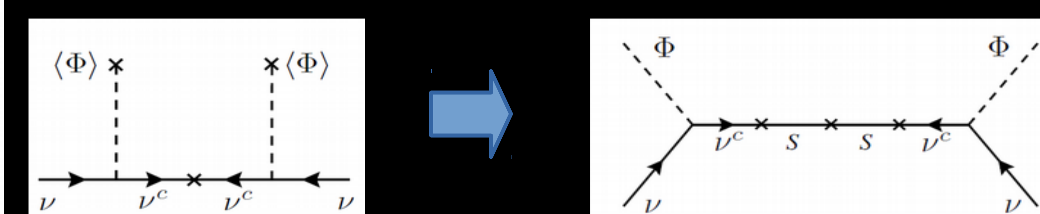


from LEP to LHC



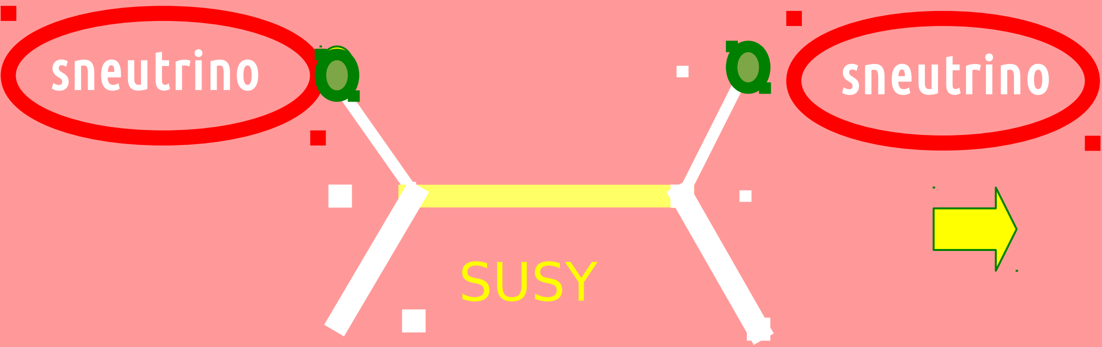


high vs low scale seesaw



susy origin of neutrino mass

Masiero & Valle, PLB251 (1990) 273
Bhattacharyya & Pal, PRD82 (2010) 055013



EFF. BILINEAR RPV

ATM SCALE
SUSY-SEESAW

Diaz et al PRD68 (2003) 013009, PRD62 (2000) 113008

Bazzocchi et al JHEP 01 (2013) 033 arXiv:1202.1529

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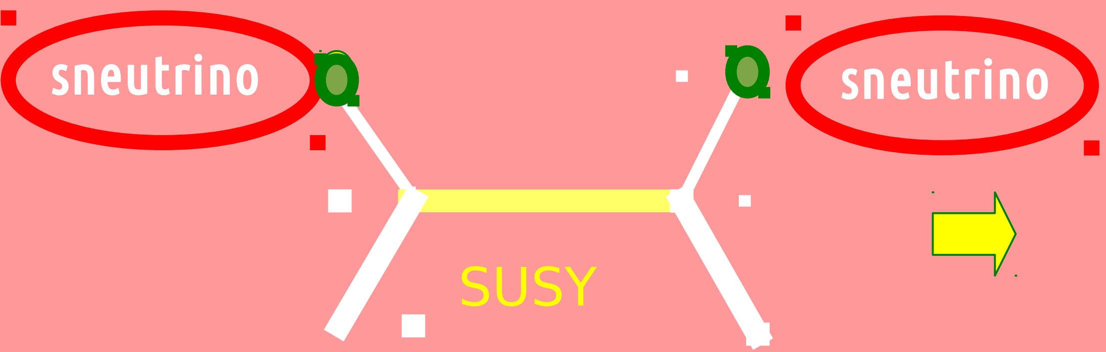
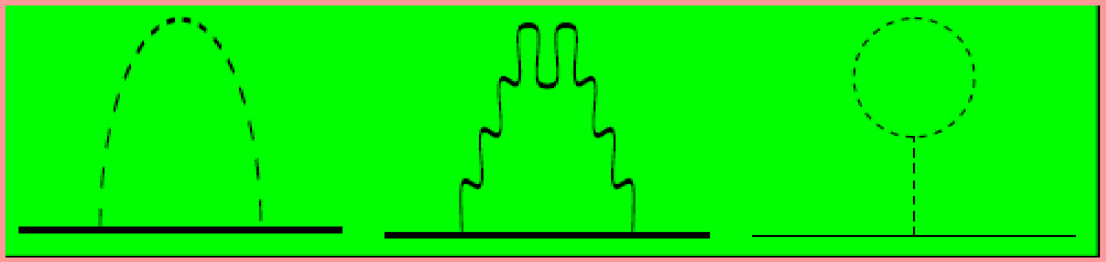


EFF. BILINEAR RPV

ATM SCALE
SUSY-SEESAW



SOLAR SCALE
RADIATIVE

Diaz et al PRD68 (2003) 013009, PRD62 (2000) 113008

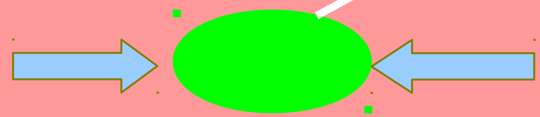
Bazzocchi et al JHEP 01 (2013) 033 arXiv:1202.1529

LIGHTEST NEUTRALINO DECAYS from cascade squark & gluino decays

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

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

$$\tilde{\chi}_1^0 \to Z^0 \nu_i$$



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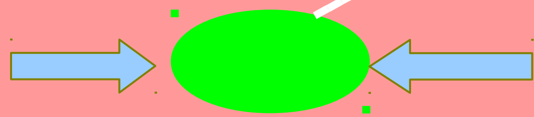
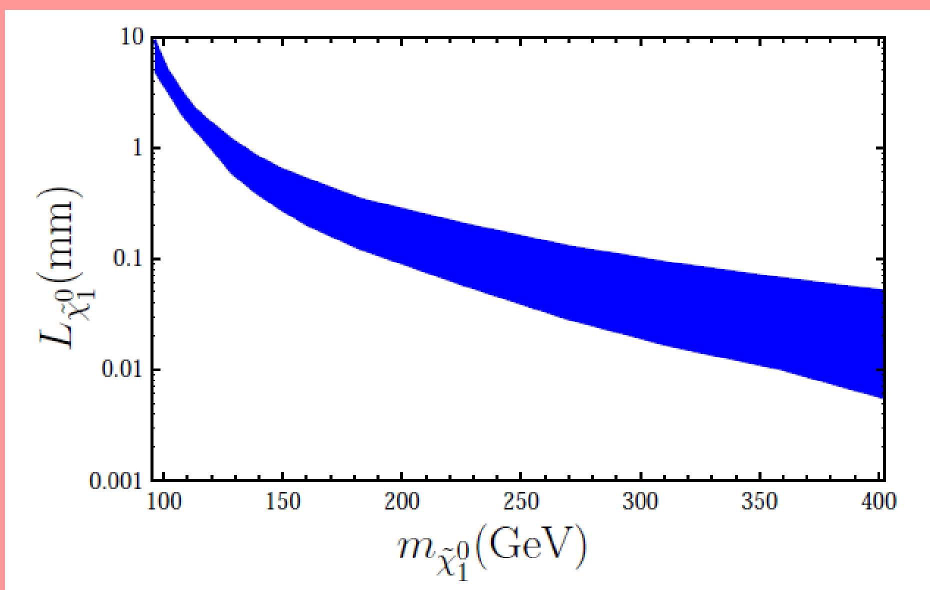


Lightest neutralino decay length



LIGHTEST NEUTRALINO DECAYS from cascade squark & gluino decays

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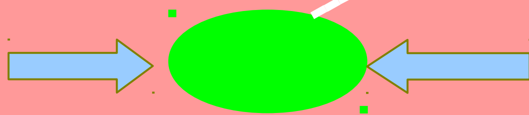
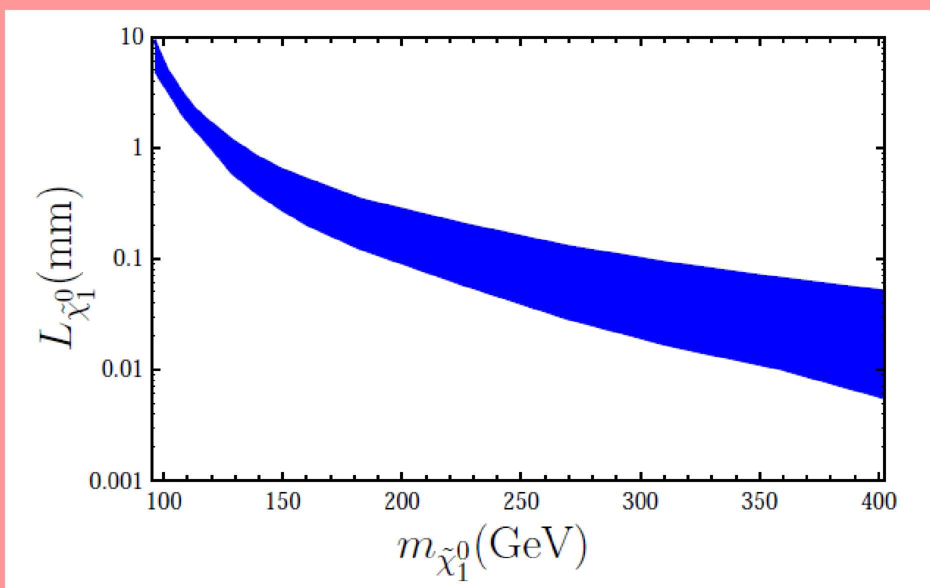
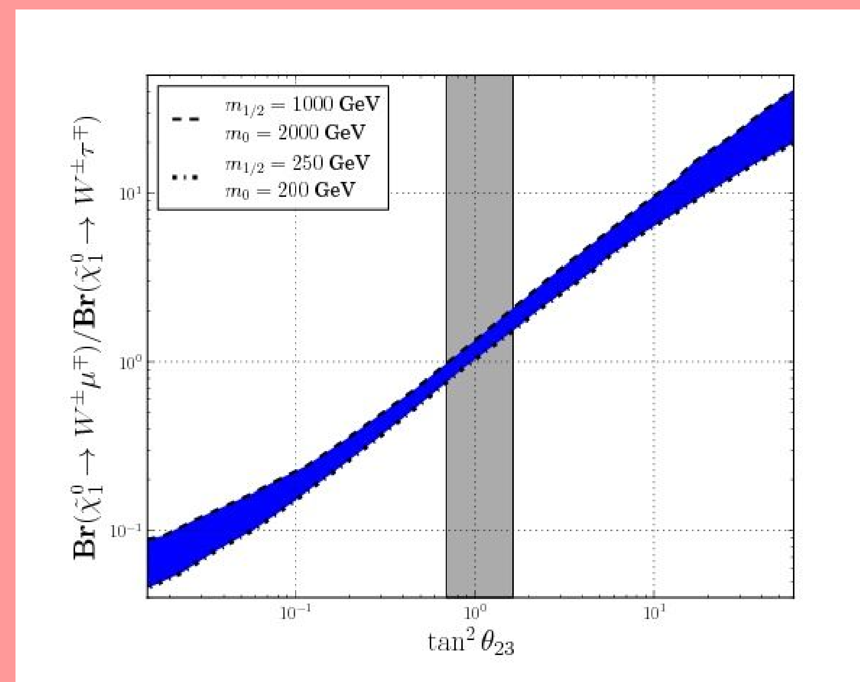


Lightest neutralino decay correlates with atm angle

Lightest neutralino decay length





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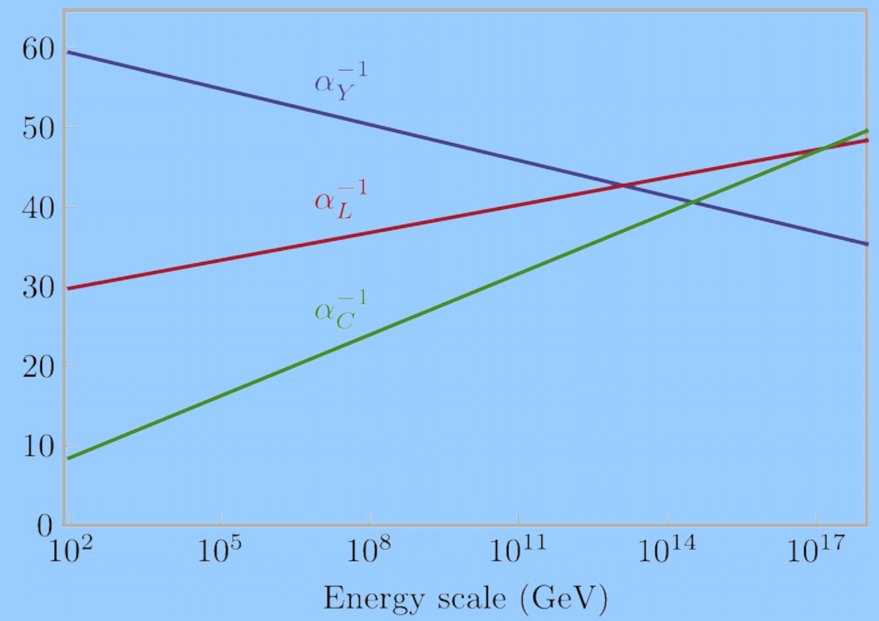
PROBING NUS @ LHC

Standard model

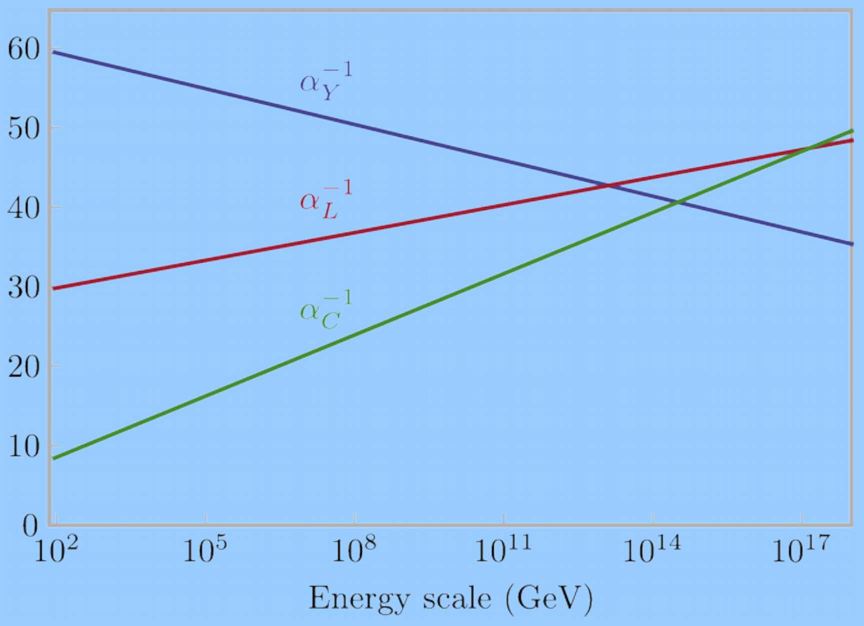
a near miss ...



SUSY would make the gauge couplings unify at GUT scale,
But … so far no p decay nor super-partners ...

Standard model

a near miss ...



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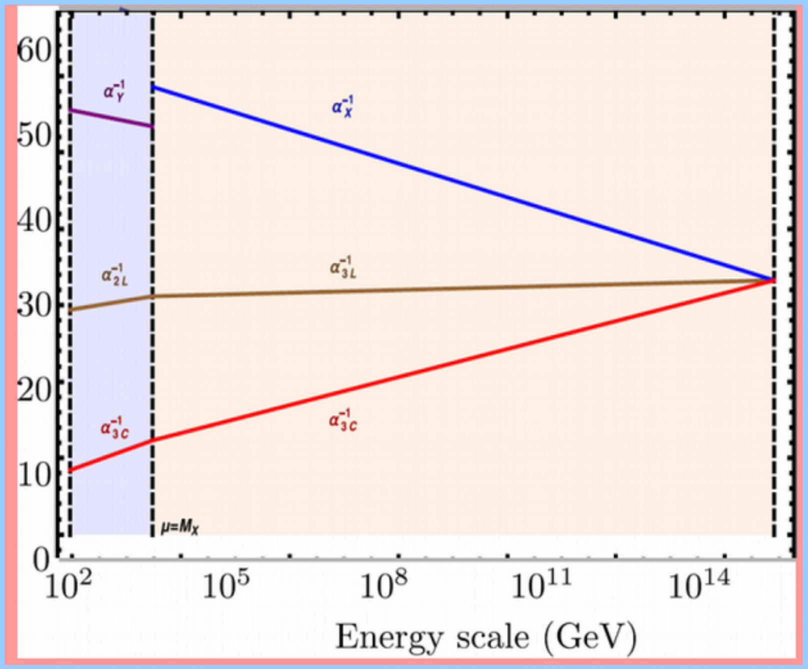


neutrinos & 331 unification

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

E(6) F-theory GUT ⇨ 331-EW theory

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

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

radiative neutrino mass

in low scale 331 EW theory

331 motivation # families = # colours

Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

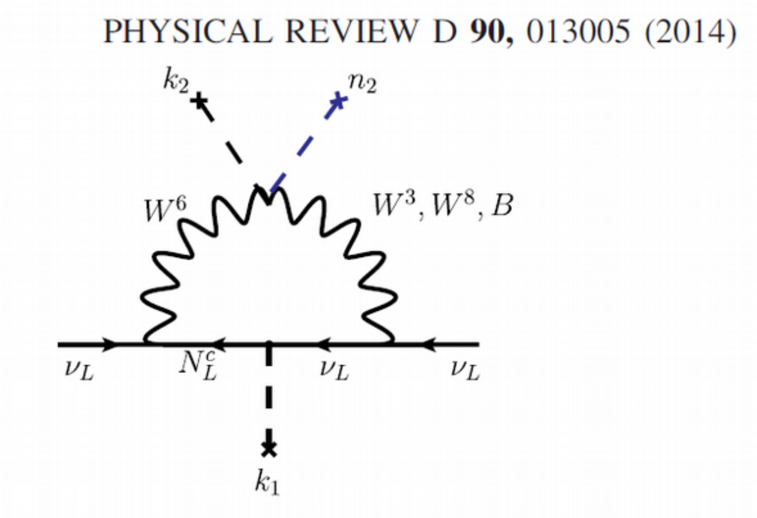
radiative neutrino mass

in low scale 331 EW theory

331 motivation # families = # colours

Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

Gauge vs Higgs origin



Boucenna, Morisi, JV Phys.Rev. D90 (2014) 013005

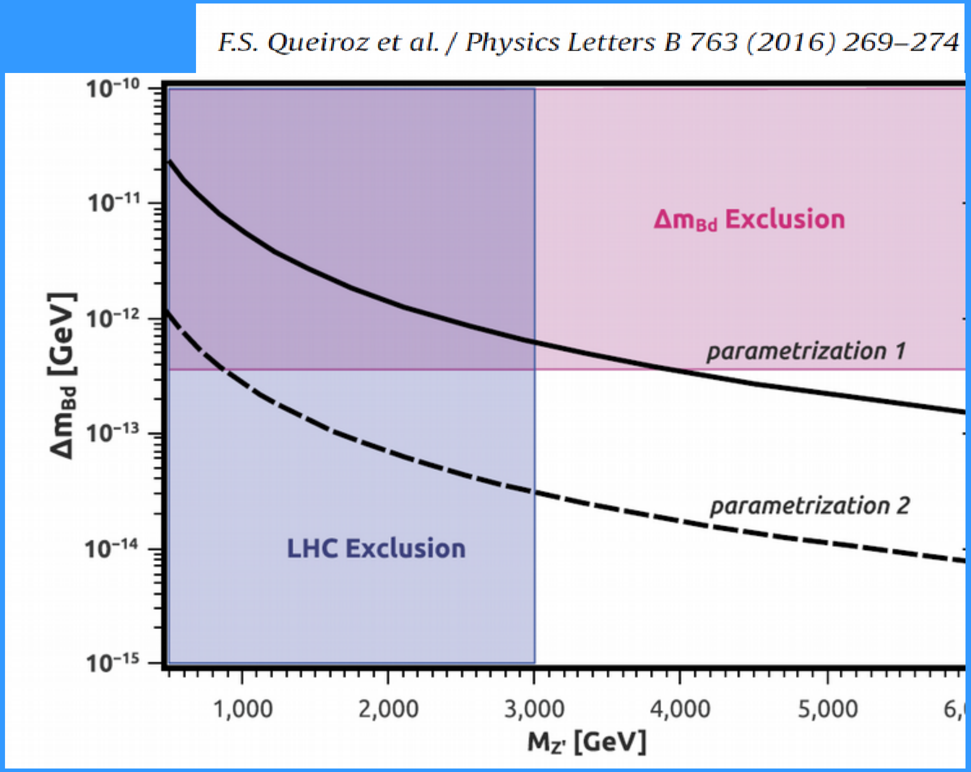
radiative neutrino mass

in low scale 331 EW theory

331 motivation

families = # colours

Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738



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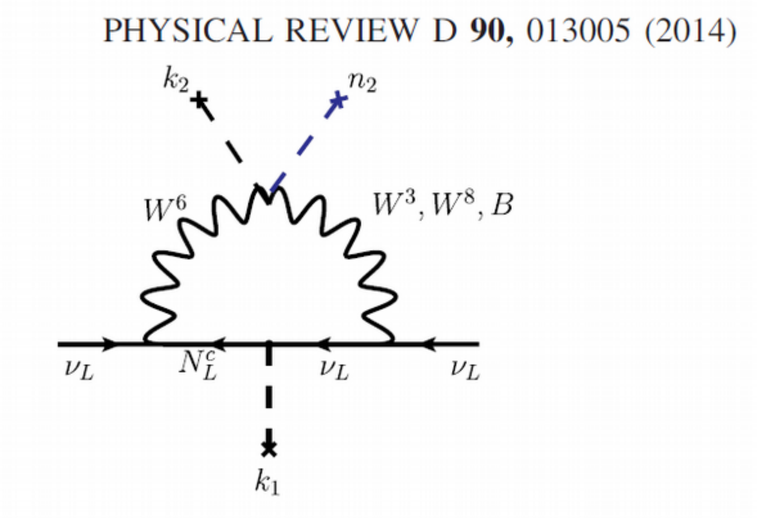
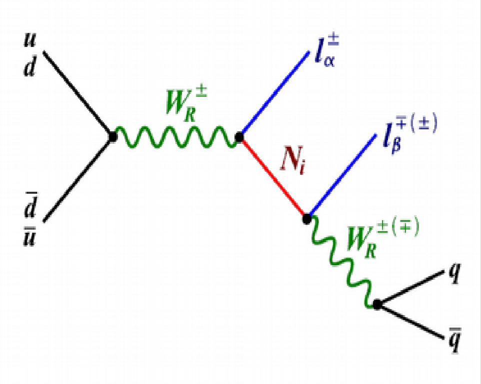
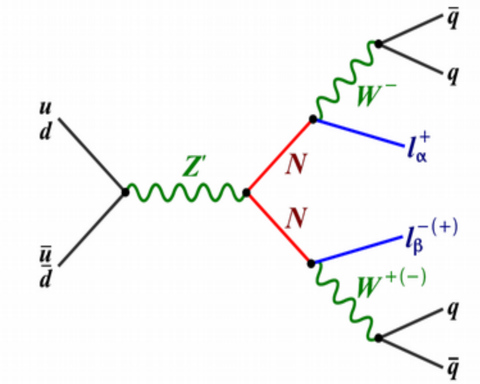


Boucenna, Morisi, JV Phys.Rev. D90 (2014) 013005

seesaw mediator searches with new gauge portal

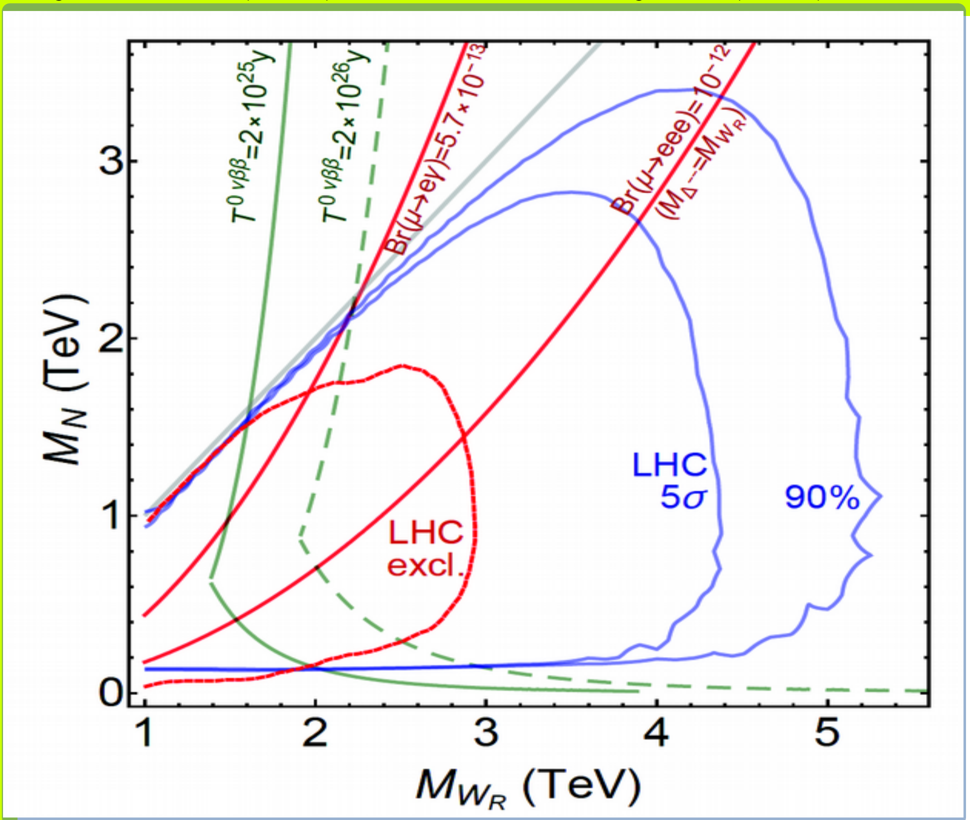


extended EW theory at LHC

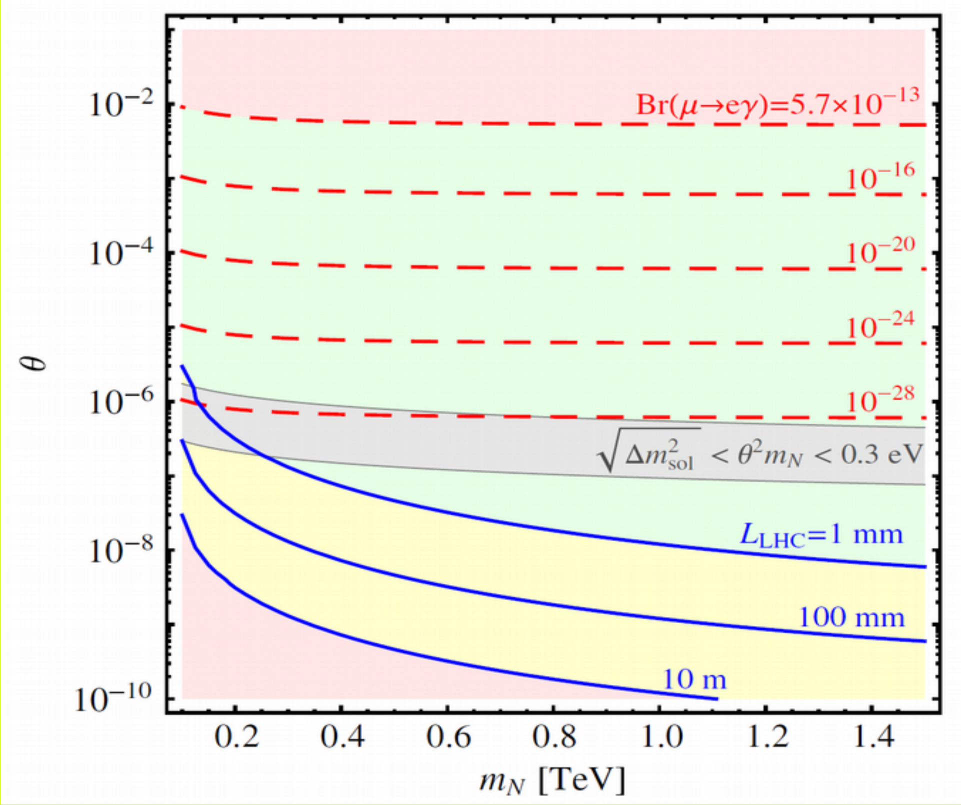


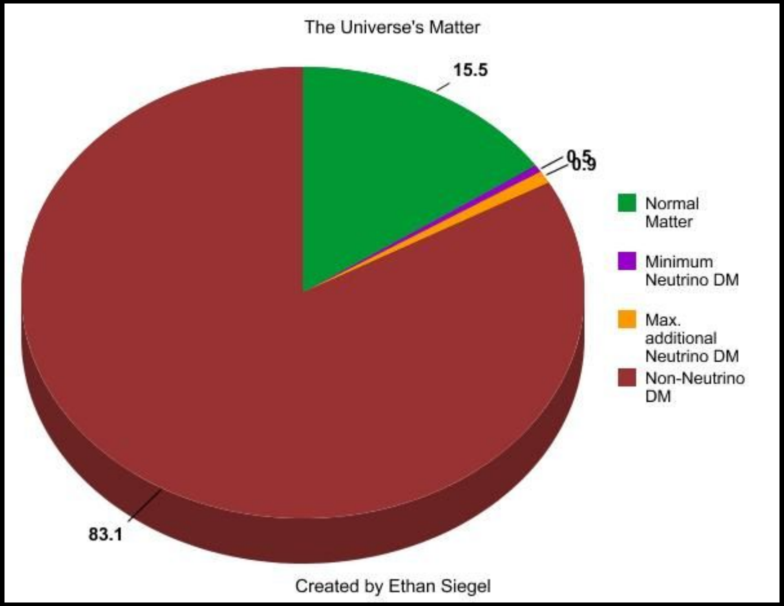
lepton flavor violation as a HE phenomenon?

Phys.Rev. D86 (2012) 055006 & New J.Phys. 17 (2015) 075019



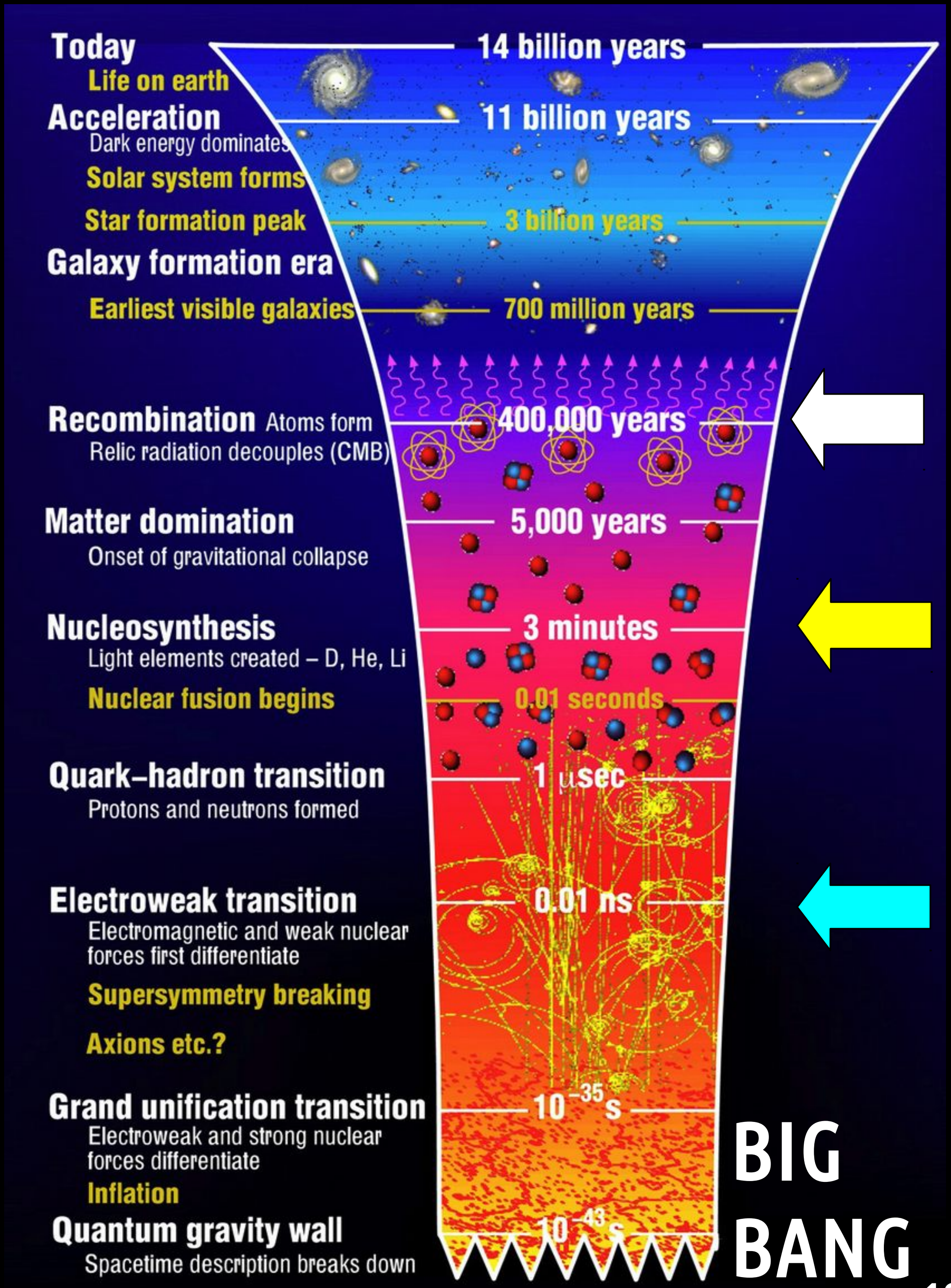
Phys.Rev. D89 (2014) 051302





need for dark matter

nu's at most 1% but can be key to DM

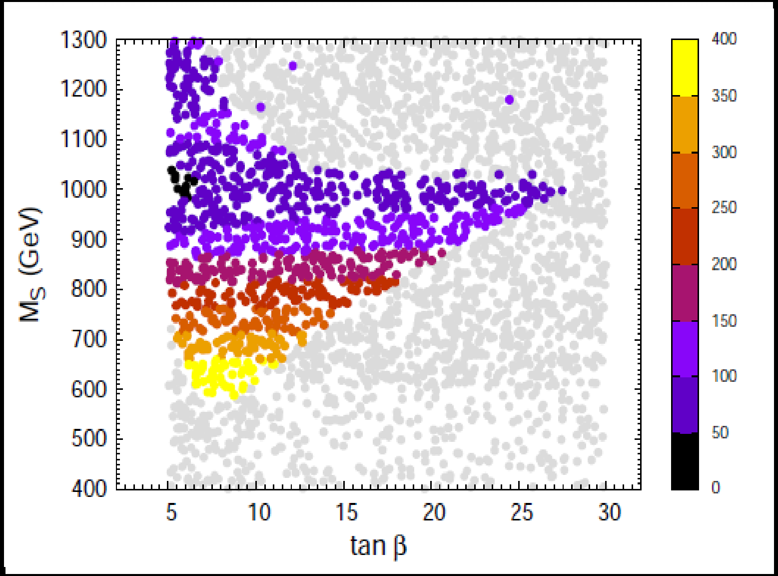


SUSY WIMP AS COLD DARK MATTER

If neutrinos get mass a
la Inverse seesaw susy
Spectrum can change so ...

LSP is SNEUTRINO-like
instead of neutralino ..

Arina et al PRL101 (2008) 161802
Bazzocchi, Cerdeno, Munoz, JV, PRD81 (2010) 051701



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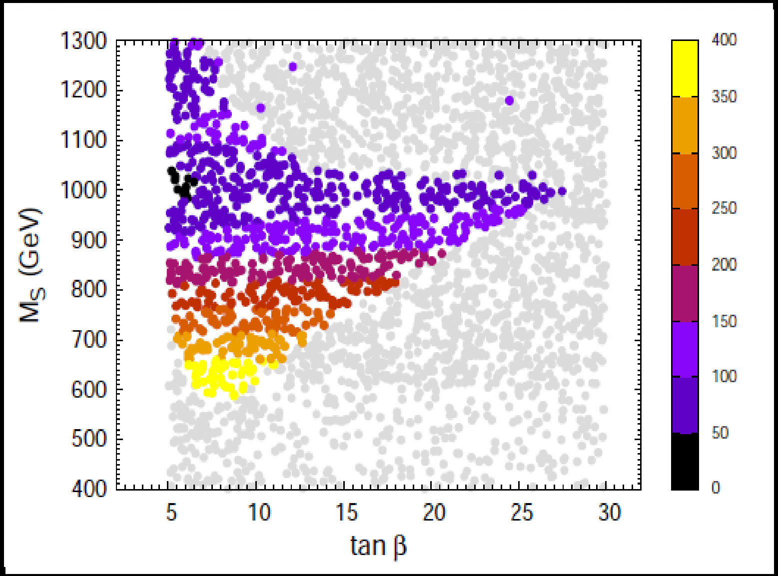

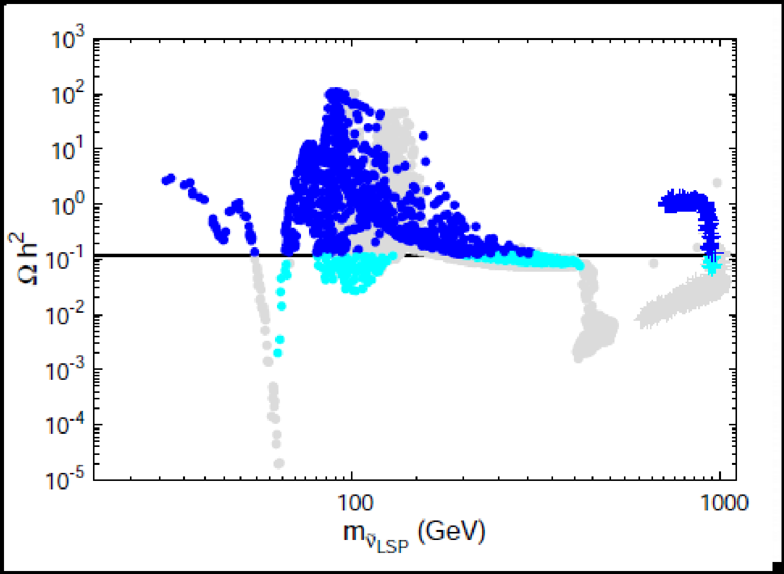

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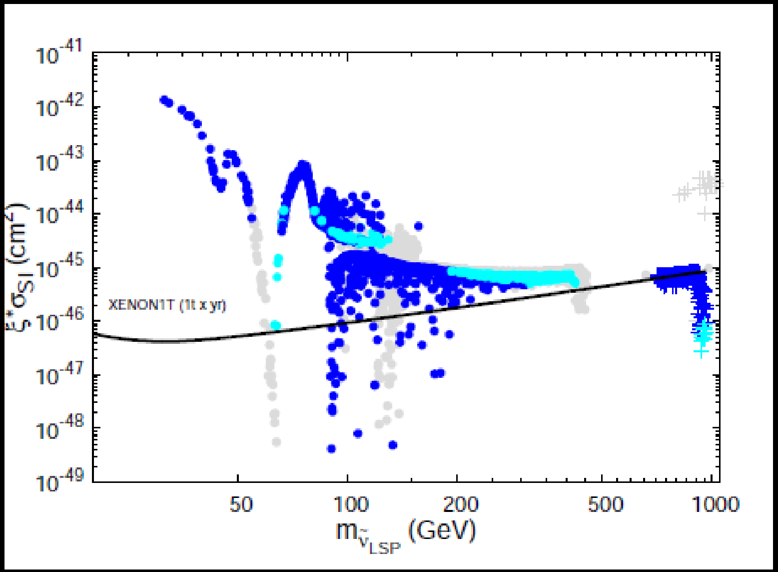
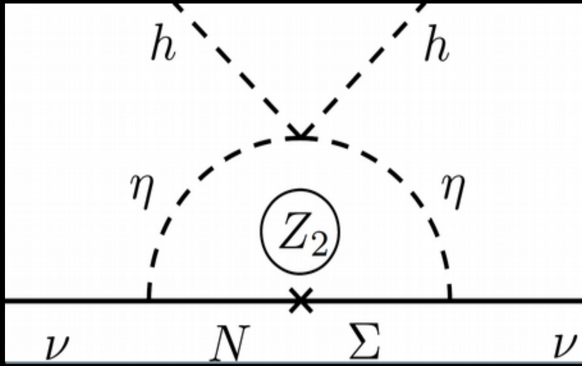
De Romeri, Patel, Valle arXiv:1808.01453





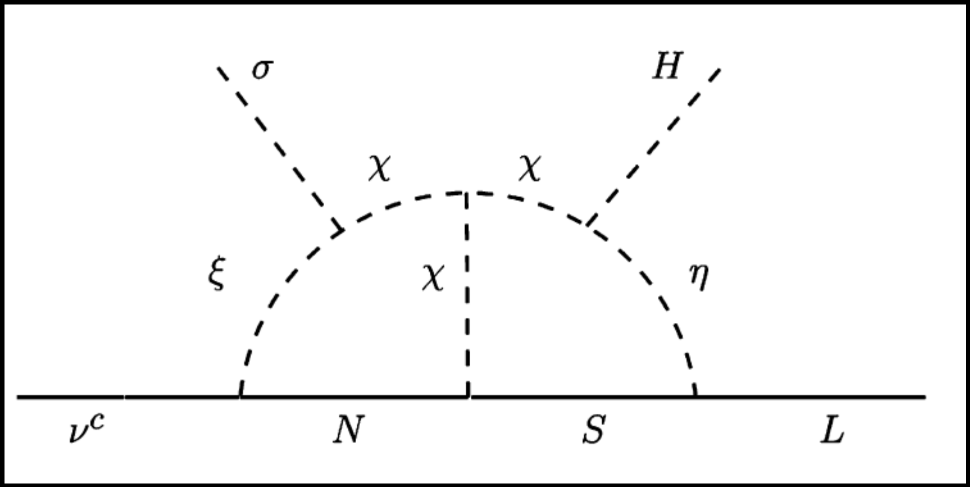
neutrino mass messenger
WIMP as dark matter

E Ma 2006 "scotogenic"

Hirsch et al JHEP 1310 (2013) 149
Merle et al JHEP 1607 (2016) 013
Diaz et al JHEP01(2016)007

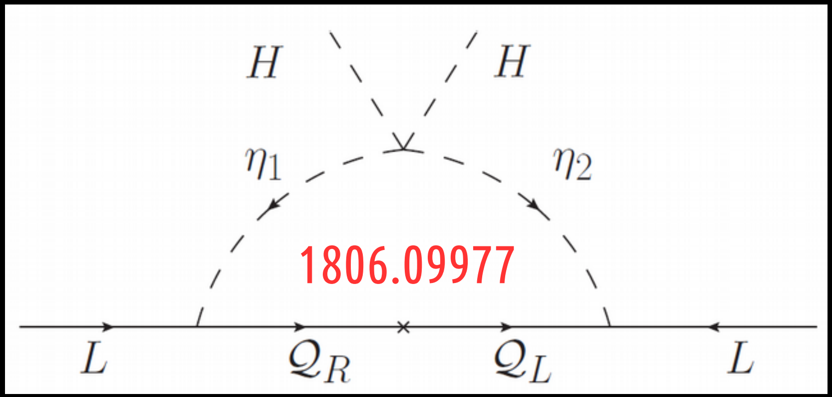
Z2 preserved by RGE

many variants, e.g.



Phys.Lett. B762 (2016) 214-218

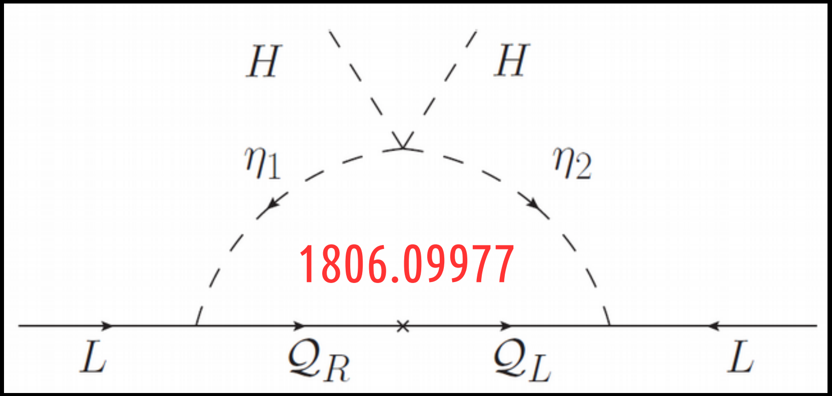
dark matter as bound-state of neutrino mass messenger



Reig, Restrepo, Valle, Zapata

De Luca, Mitridate, Redi, Smirnov, Strumia

dark matter as bound-state of neutrino mass messenger



Reig, Restrepo, Valle, Zapata

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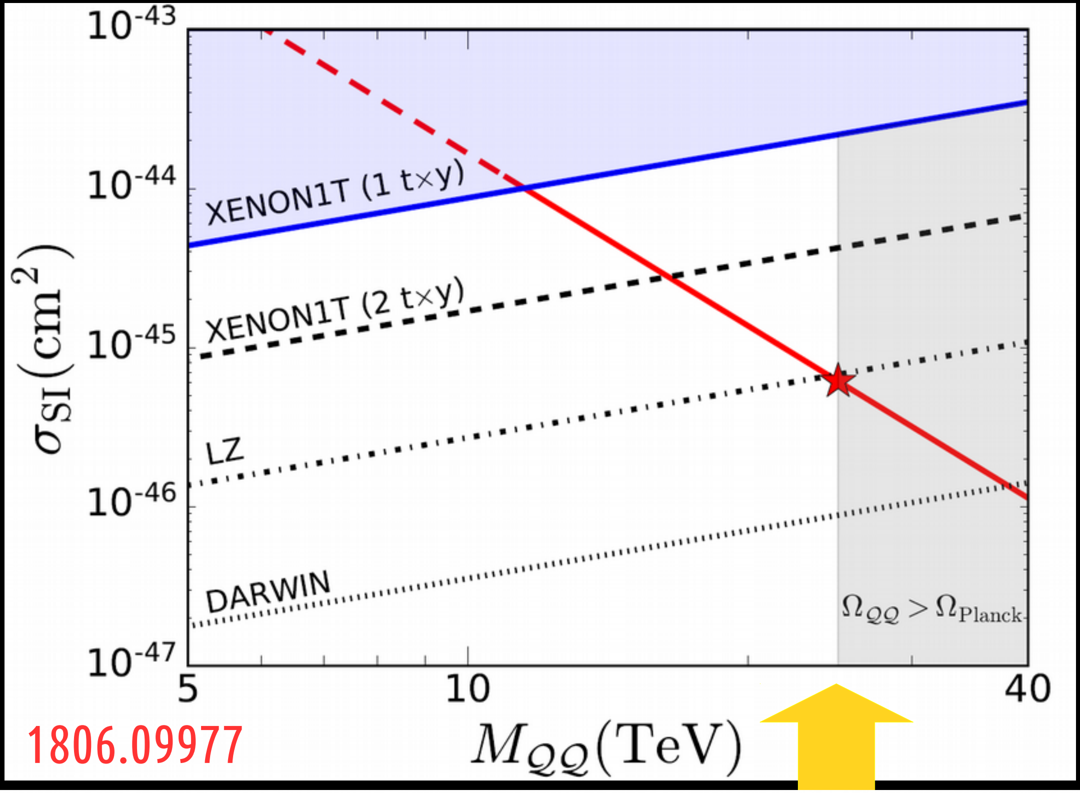

FIG. 2. Spin-independent cross section as a function of $M_{QQ} = 2M_Q$ (red). The star represents the mass required for a thermal bound state 25 TeVdark matter. Lower values can be probed by direct searches, the current bound is indicated in blue, while the black lines (dashed, dotted and dot-dashed) correspond to future sensitivities.

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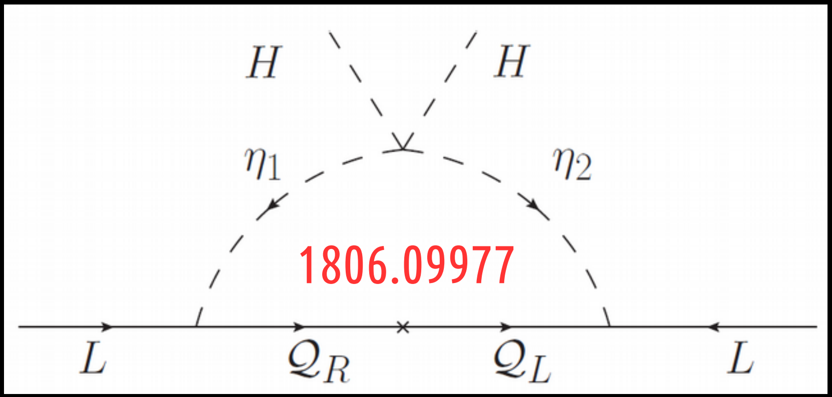
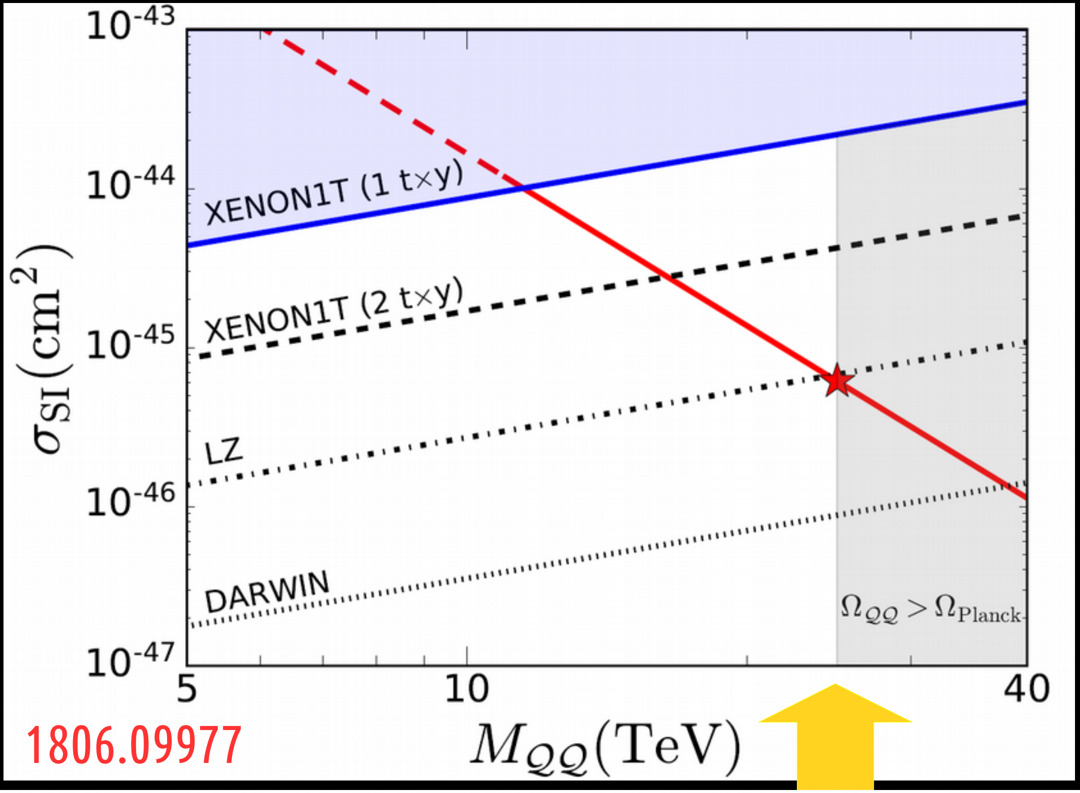
dark matter as bound-state of neutrino mass messenger



Reig, Restrepo, Valle, Zapata

De Luca, Mitridate, Redi, Smirnov, Strumia



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Phys.Rev. D97 (2018) 115032

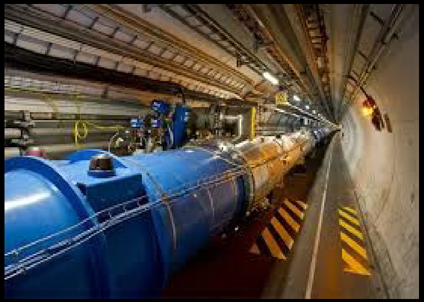
DM stability from Diracness

detecting messengers & measuring angles @ high energies

neutrinos lie at the center of particle physics, e.g. EWSB

detecting messengers & measuring angles @ high energies

neutrinos lie at the center of particle physics, e.g. EWSB

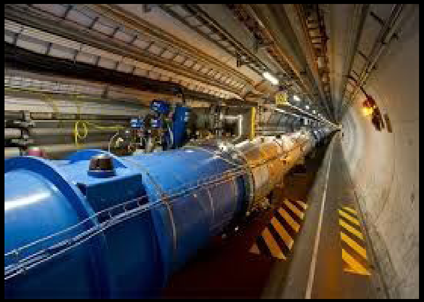


comprehensive

flavor theory
with new physics
above 10 TeV

detecting messengers & measuring angles @ high energies

neutrinos lie at the center of particle physics, e.g. EWSB



comprehensive

flavor theory with new physics above 10 TeV

cosmology as emergent theory implies new physics @ colliders

Sneutrino-like CWDM   Gravitino CDM

WIMP DM stability from flavor: discrete DM

WIMP DM stability from Diracness

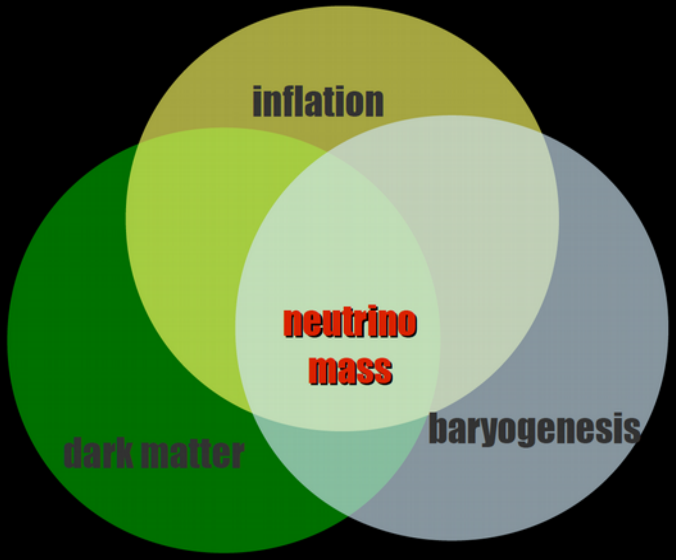
Bound-state dark matter

WIMP DM stability from gauge matter parity

DM can be warm & metastable, e.g. the majoron

majoron DM + inflation

adding dark energy   Smoot arXiv:1405.2776 etc etc



THE END

decaying Gravitino dark matter

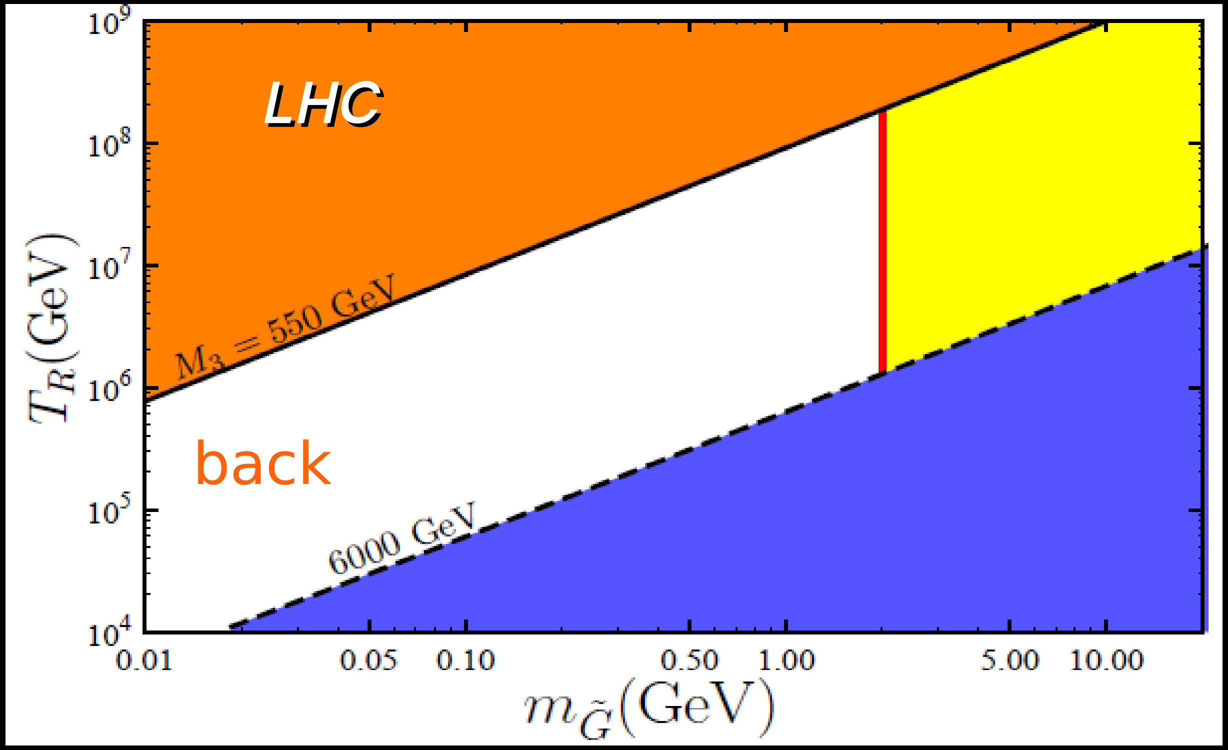
decays suppressed by Planck mass & smallness of m-nu

$$\Gamma = \Gamma(\tilde{G} \to \sum_i \nu_i \gamma) \simeq \frac{1}{32\pi} |U_{\tilde{\gamma}\nu}|^2 \frac{m^3_{\tilde{G}}}{M_P^2}$$

chosen to fit neutrino osc. data

Restrepo et al
PRD85 (2012) 023523

relic abundance
+ LHC searches



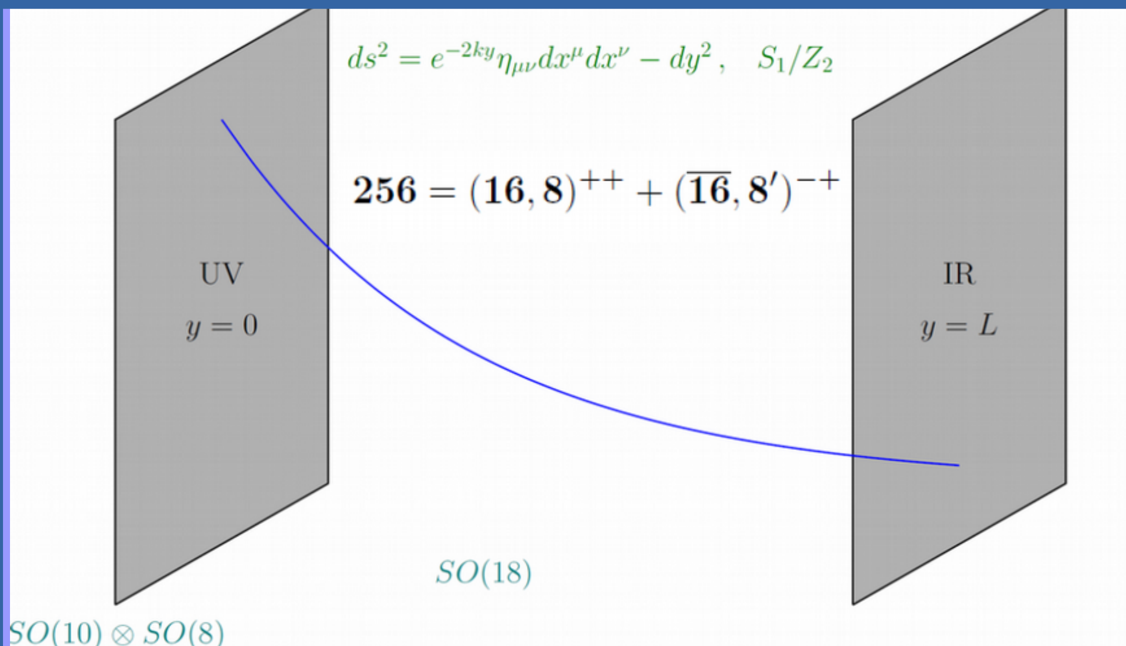
excluded by gamma
line searches @
Egret & Fermi-LAT

Unifying forces & families

inspired by beauty of neutrinos in SO10

$$\mathbf{16} \to (\mathbf{3}, \mathbf{2}, 1/6) + (\mathbf{1}, \mathbf{2}, -1/2) + (\bar{\mathbf{3}}, \mathbf{1}, 1/3) + (\bar{\mathbf{3}}, \mathbf{1}, -2/3) + (\mathbf{1}, \mathbf{1}, 1) + (\mathbf{1}, \mathbf{1}, 0)\,,$$

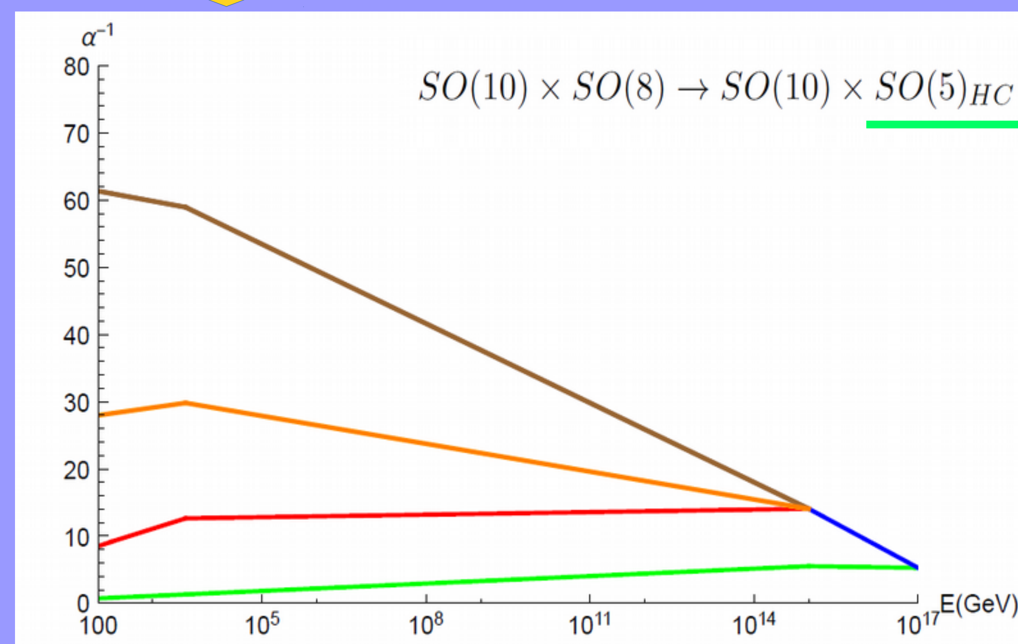
Reig, Valle, Vaquera-Araujo, Wilczek
Phys.Lett. B774 (2017) 667-670



promote M4 to AdS5 & use orbifold BC to decouple mirrors

unwanted chiral families bound by new hypercolor force above TeV

new spectroscopy



SO(3) family symmetry

Reig, JV, Wilczek
arXiv:1805.08048

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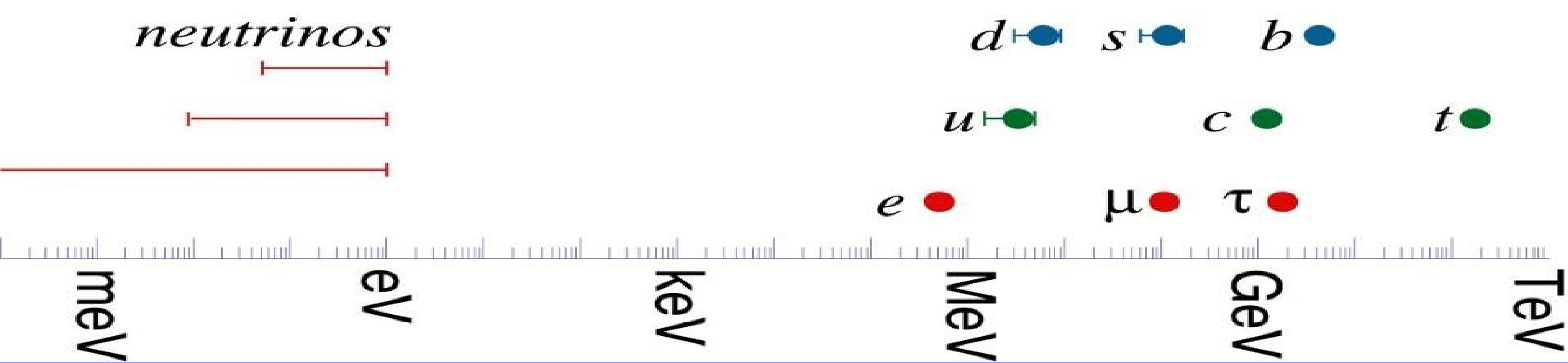
	q_L	u_R	d_R	l_L	e_R	ν_R	Φ^u	Φ^d	Ψ^u	Ψ^d	σ	ρ
$SU(3)_c$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**2**	**2**	**2**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	0	0
$SO(3)_F$	**3**	**3**	**3**	**3**	**3**	**3**	**5**	**5**	**3**	**3**	**5**	**1**
$U(1)_{PQ}$	1	-1	-1	1	-1	-1	2	2	2	2	2	2



from oscillations to charged fermion masses

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

Golden Q-L unification

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

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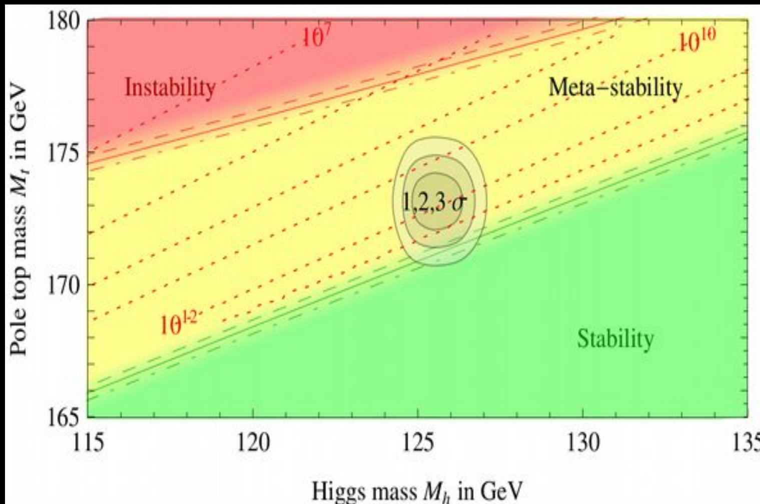
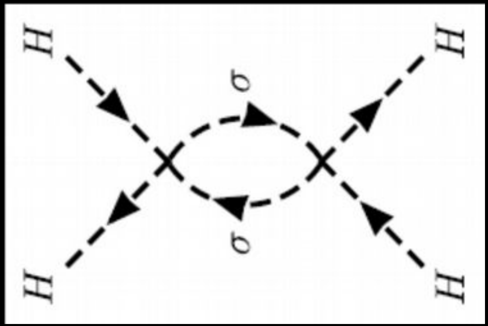


From Degrassi et al: JHEP 1208 (2012) 098

neutrinos make the EW vacuum stable again

Phys.Rev. D92 (2015) 075028

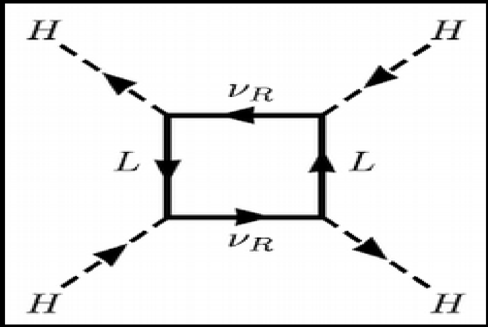


Higgs searches **Bonilla et al**

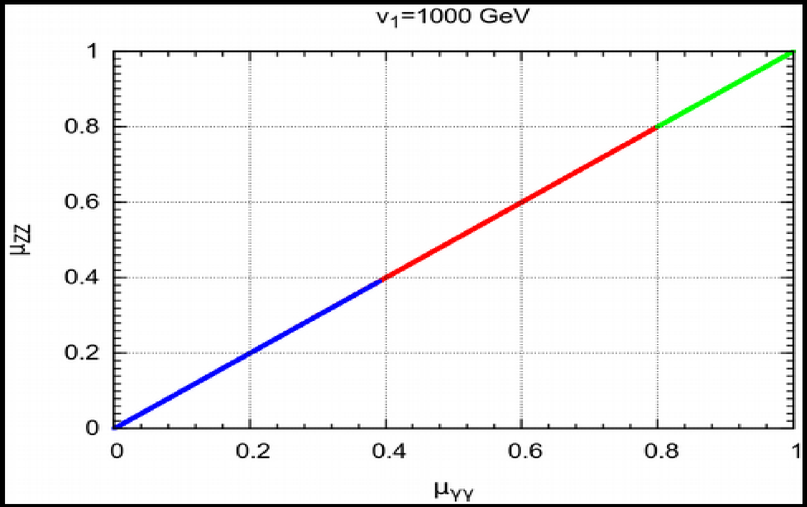
Phys.Lett. B756 (2016) 345-349

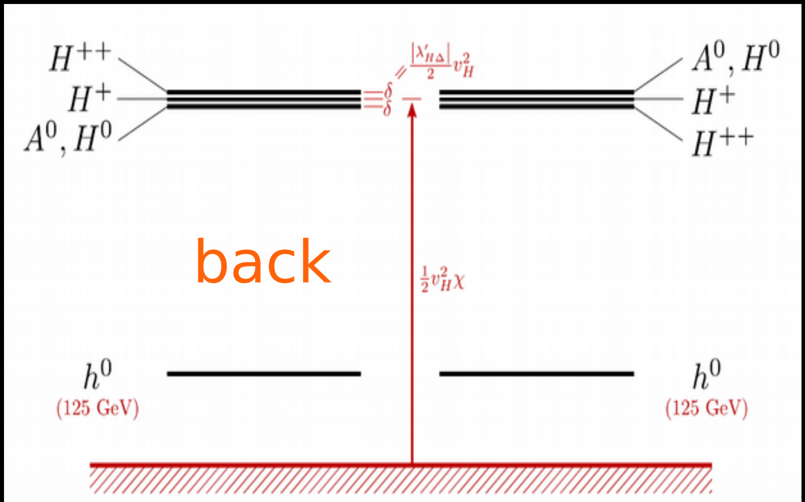
New J. Phys. 18 (2016) 033033

Phys.Rev. D91 (2015) 113015



benchmark for EW studies @ colliders





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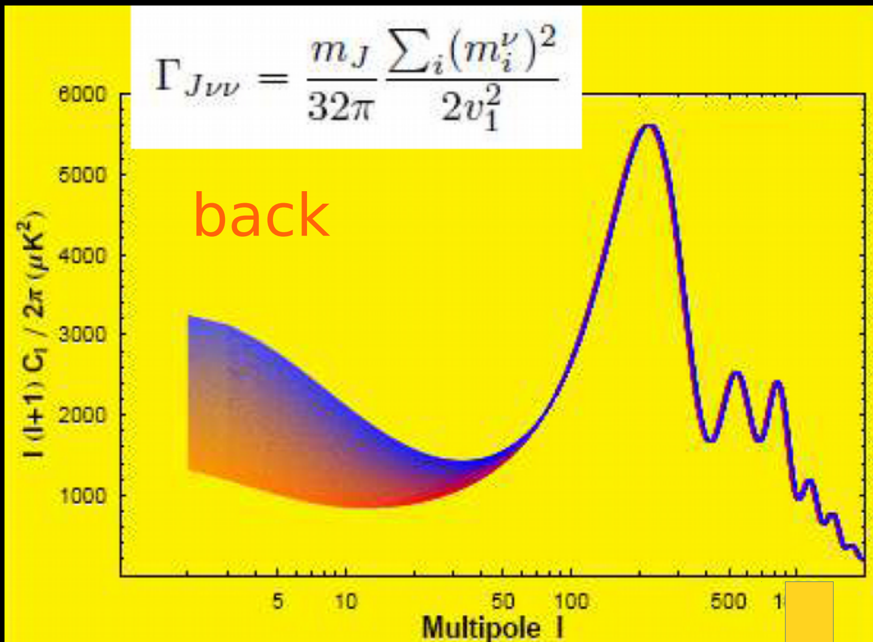
Consistency with CMB

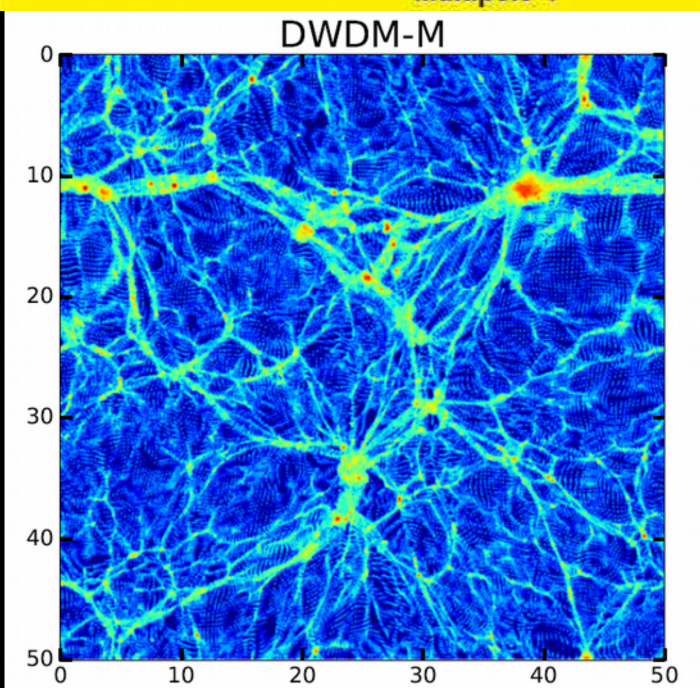
Lattanzi & Valle, PRL99 (2007) 121301

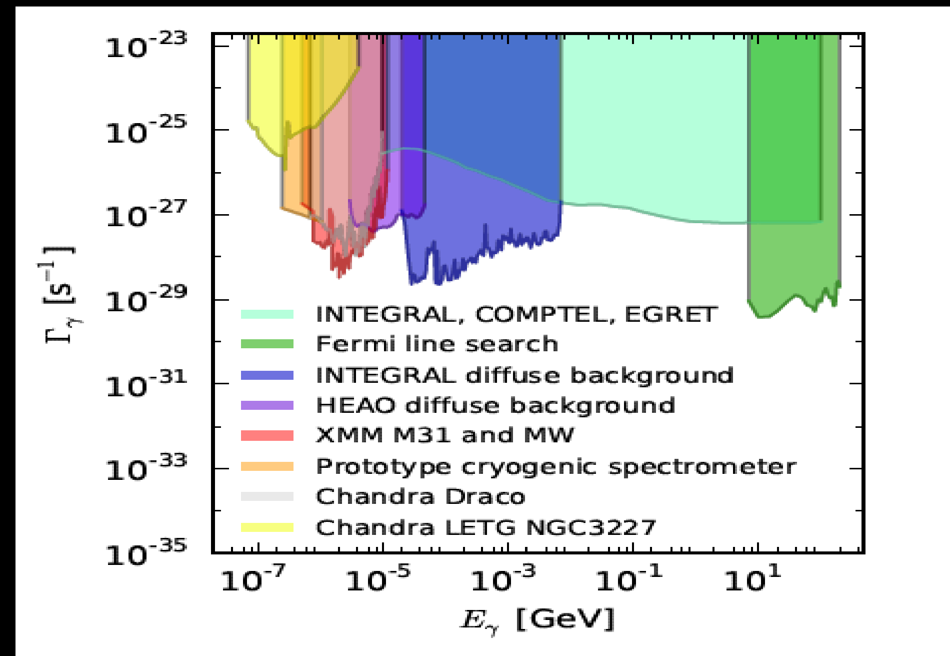
majorons as dark matter

Berezinsky, Valle PLB318 (1993) 360

$$\Gamma_{J\nu\nu} = \frac{m_J}{32\pi}\frac{\sum_i (m_i^\nu)^2}{2v_1^2}$$







$$J \to \gamma\gamma$$

X-rays from DM decay

Bazzocchi & al JCAP 0808 (2008) 013

Esteves et al, PRD 82, 073008 (2010)

Lattanzi et al PRD88 (2013) 063528

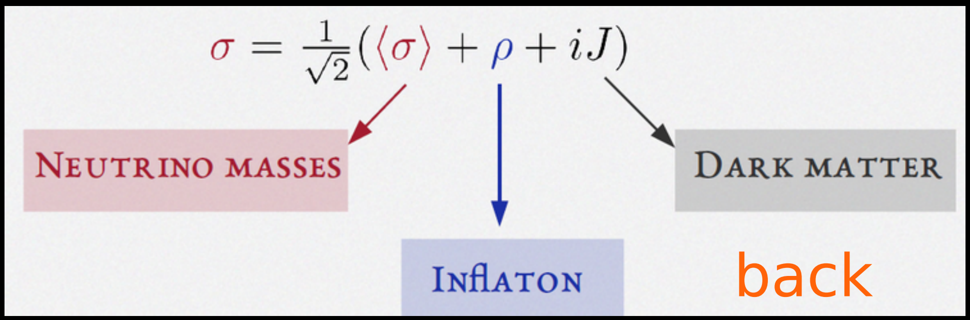
Kuo et al 1803.05650

DWDM picture leads to a viable alternative to the ΛCDM

large scale structure

majoron dark matter & seesaw inflation

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



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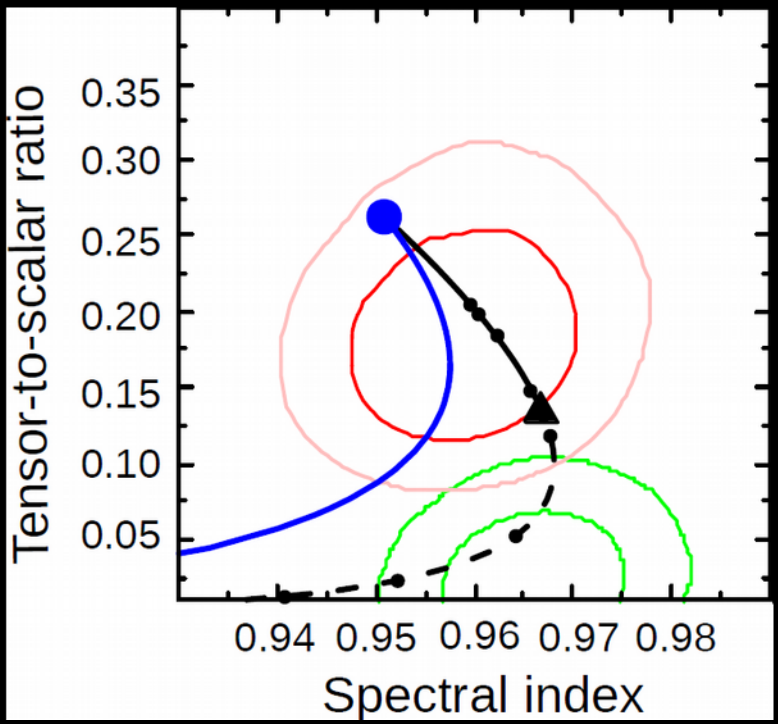
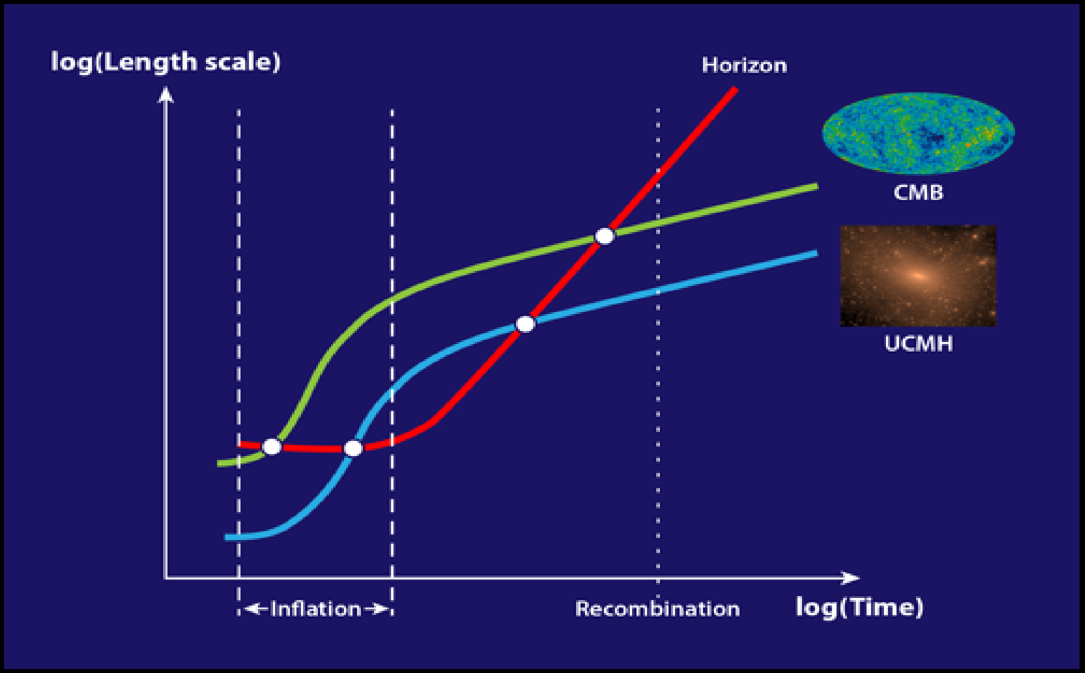
type-I seesaw **Leptogenesis**

Aristizabal et al JCAP 1407 (2014) 052

Quartic versus *Higgs Inflation*





http://arxiv.org/pdf/1502.00612v1

DM stability from gauge matter parity

Alves et al Phys.Lett. B772 (2017) 825–83

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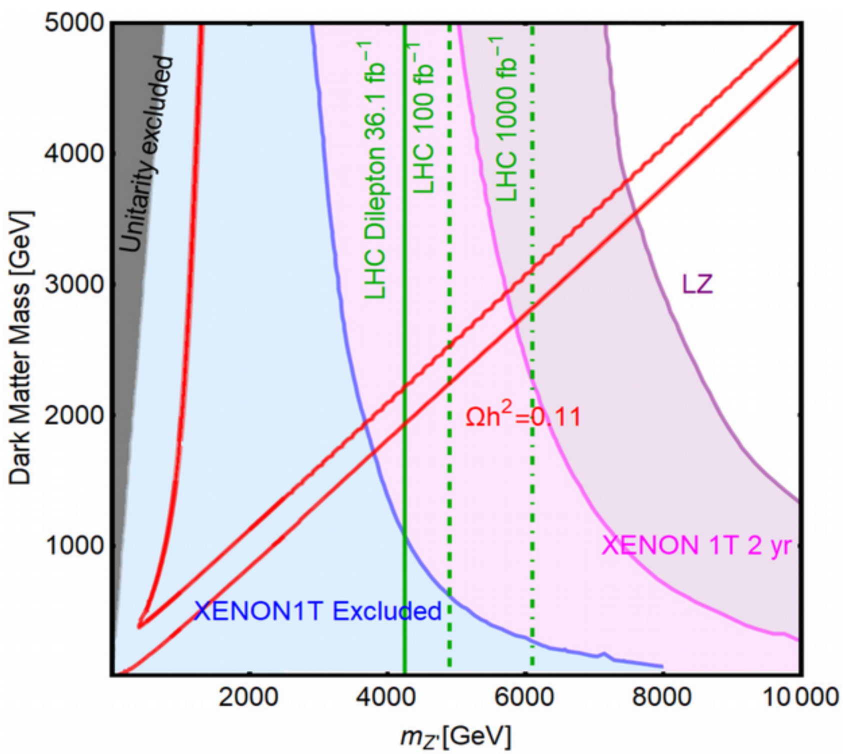
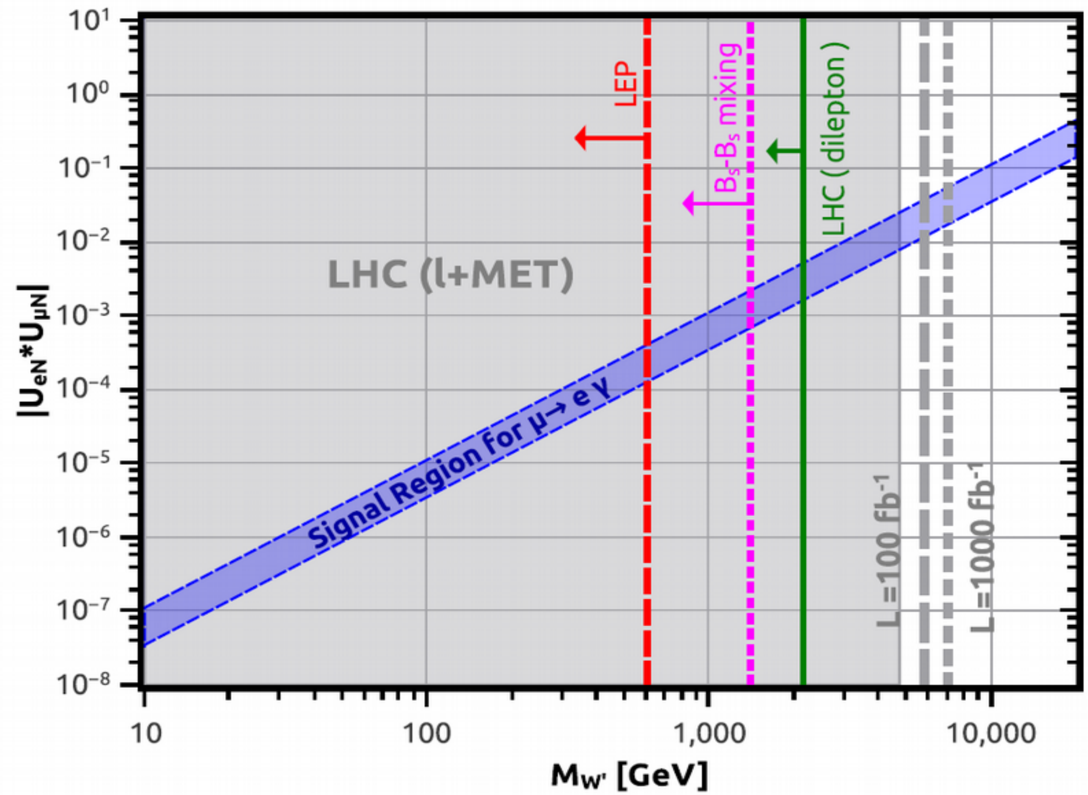
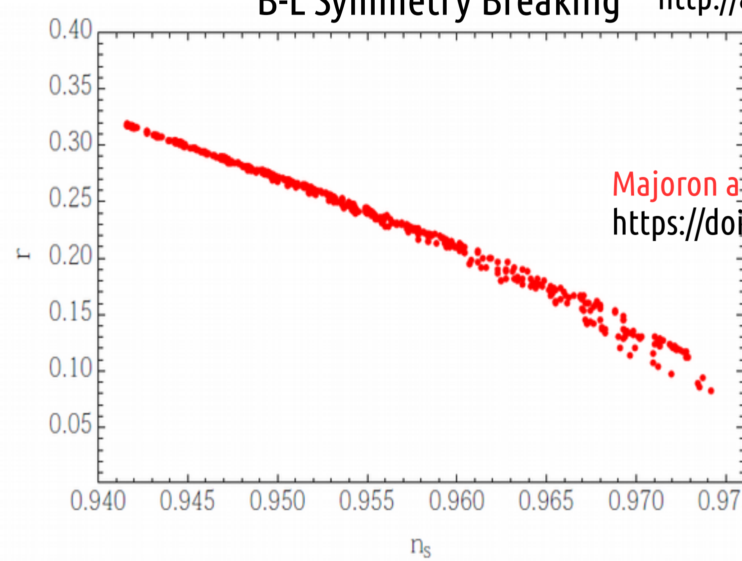


Matter-parity as a residual gauge symmetry: Probing a theory of cosmological dark matter 3-3-1-1 EW extension



Asymmetric Dark Matter, Inflation and Leptogenesis from B-L Symmetry Breaking http://arxiv.org/abs/arXiv:1805.08251



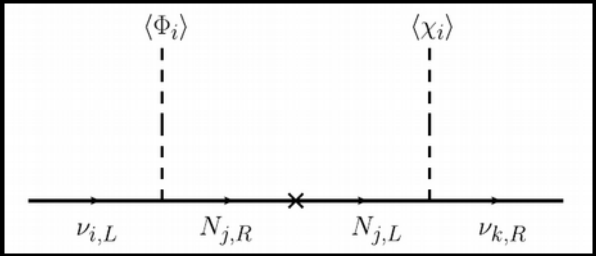
Majoron alternative
https://doi.org/10.1103/PhysRevD.90.055023

cosmology from seesaw

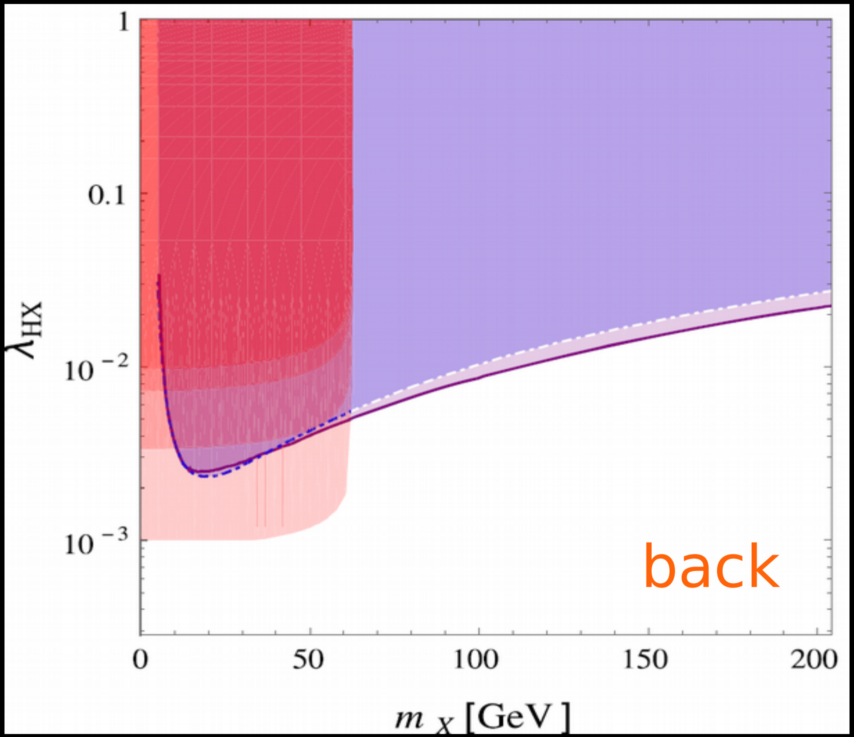
Fields	Z_4	Z_2	Fields	Z_4	Z_2
$\bar{L}_{i,L}$	$\mathbf{z}^3$	1	$\nu_{i,R}$	$\mathbf{z}$	-1
$l_{i,R}$	$\mathbf{z}$	1	$\bar{N}_{i,L}$	$\mathbf{z}^3$	1
$N_{i,R}$	$\mathbf{z}$	1			
Φ	1	1	χ	1	-1
ζ	$\mathbf{z}$	1	η	$\mathbf{z}^2$	1

Chiulia et al arXiv:1606.04543

Phys.Lett. B761 (2016) 431



DM Stability from Diracness



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No neutrinoless double-ββ decay

Search for neutrinoless quadruple-ββ decay

http://arxiv.org/abs/arXiv:1705.08847

WIMP DARK MATTER FROM FLAVOR SYMMETRY

- **accidental ?** Lavoura, Morisi, JV JHEP 1302(2013) 118

- **unbroken subgroup** Boucenna, et al JHEP 1105 (2011) 037
Hirsch, et al Phys.Rev. D82 (2010) 116003

A4 — many choices

↓

Z2 PARITY — more possibilities

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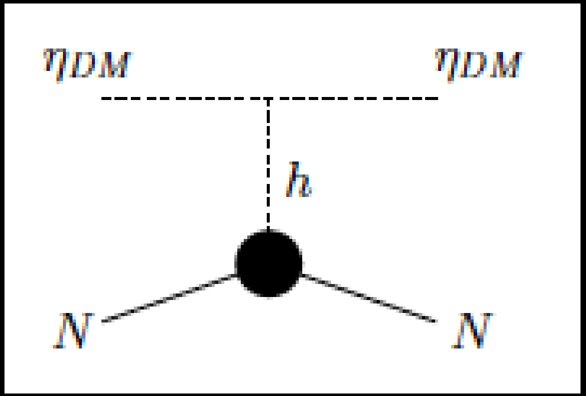

HIGGS PORTAL
DIRECT DETECTION

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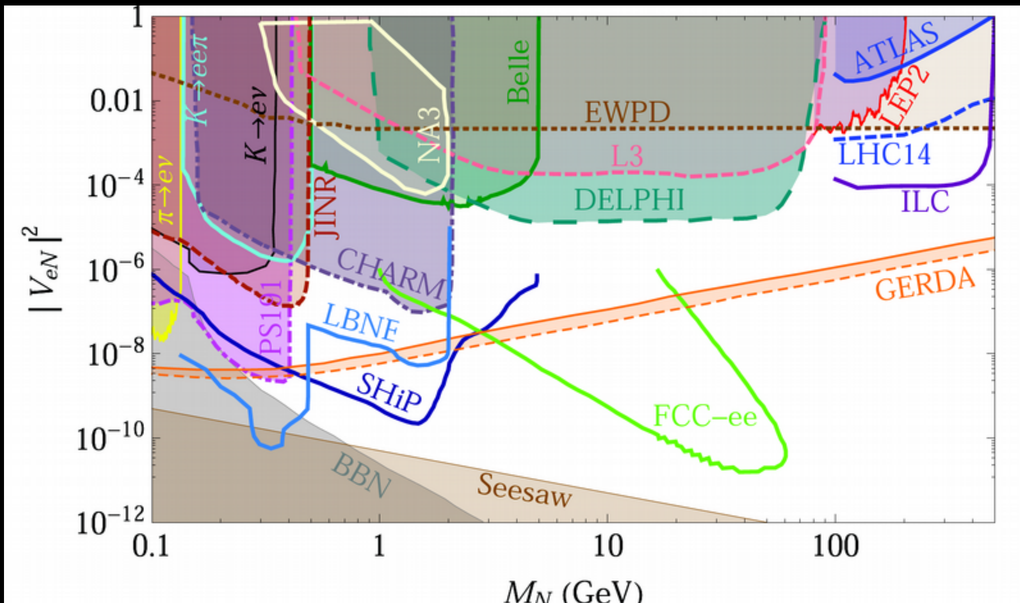
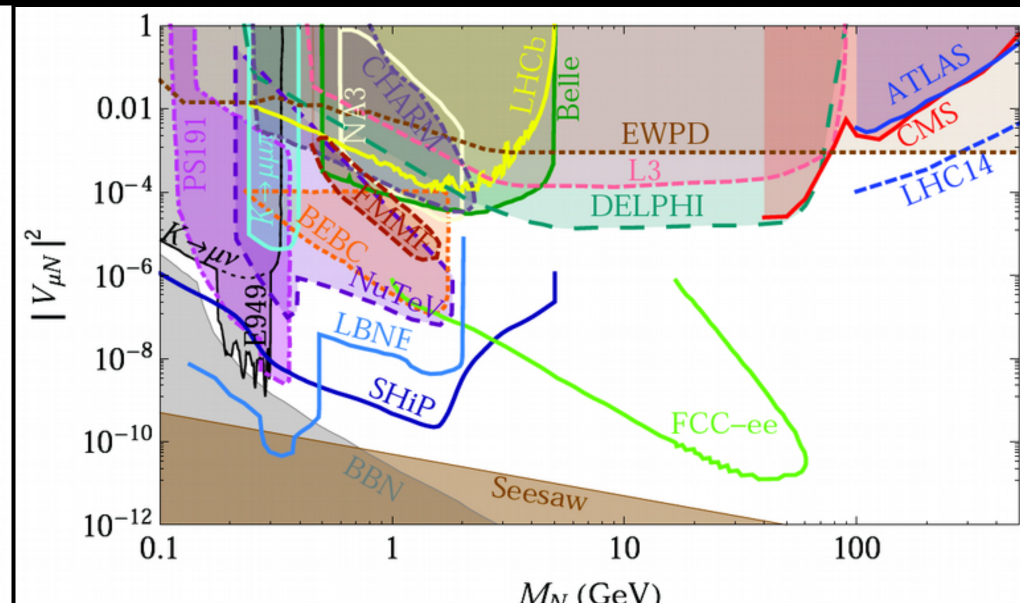
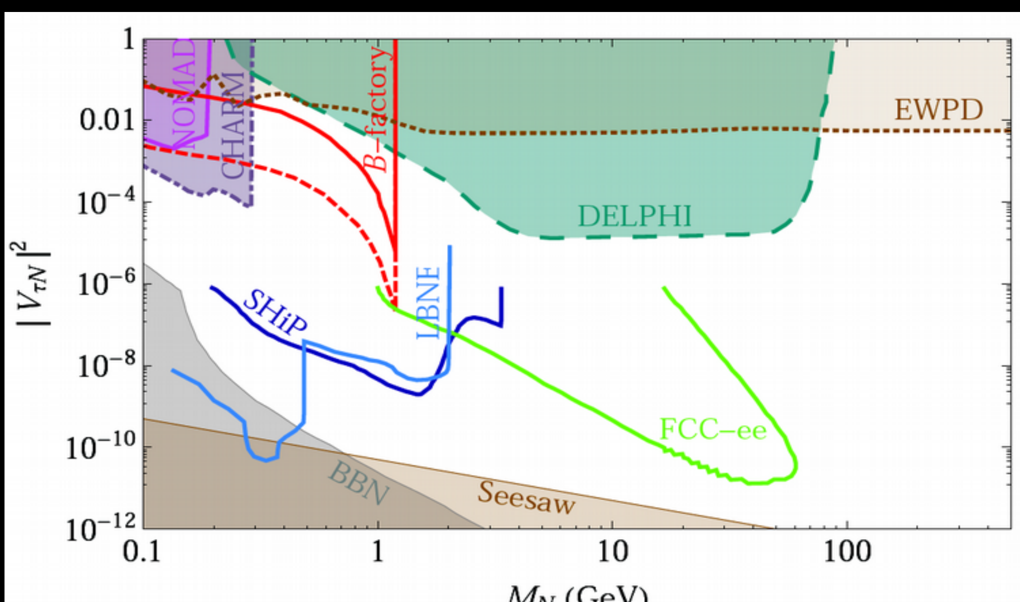
NHL in the standard model







high vs low scale seesaw