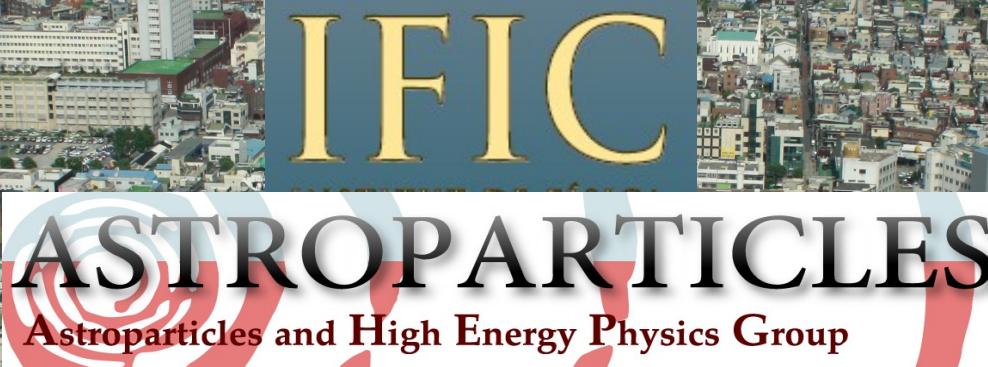


future neutrino physics outlook

JOSÉ W F VALLE



CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS



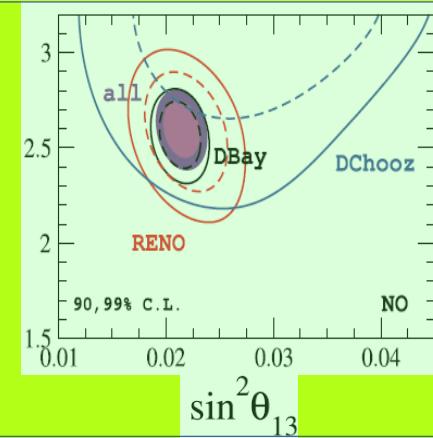
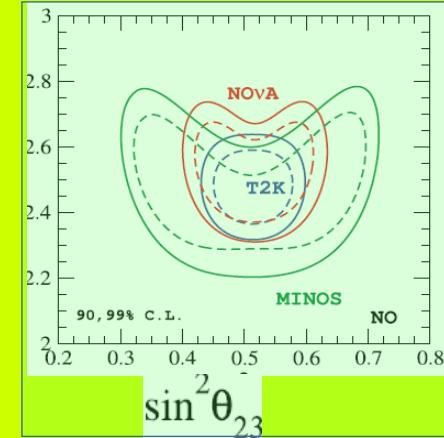
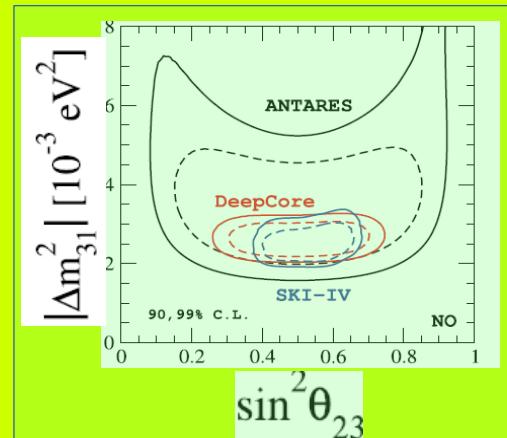
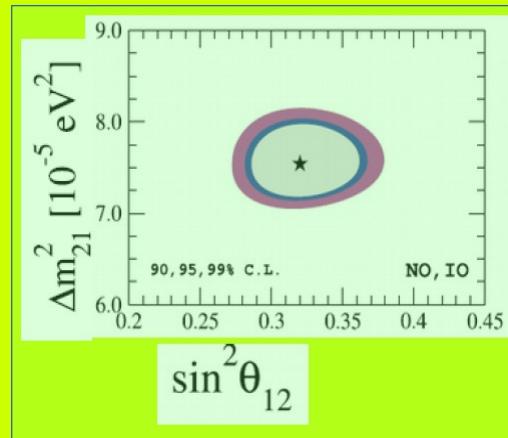
UNIVERSITAT
DE VALÈNCIA



NUFACt 2019

Daegu, Korea (August 2019)

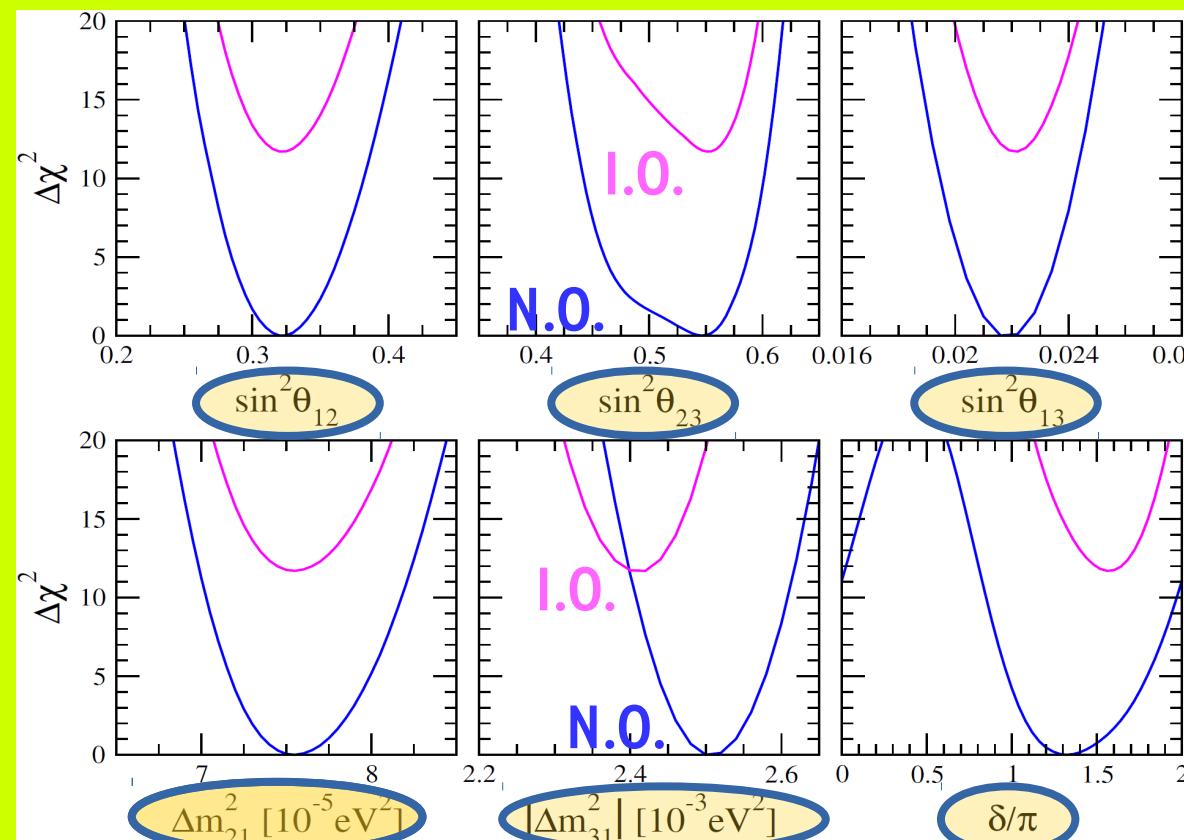
drone view of neutrino oscillations



confirm & improve
 Θ_{13} key input to many
new experiments

3-neutrino paradigm

Consistent global picture
Good agreement amongst groups
mass ordering : normal @ $> 3\sigma$



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

now the loose ends of the

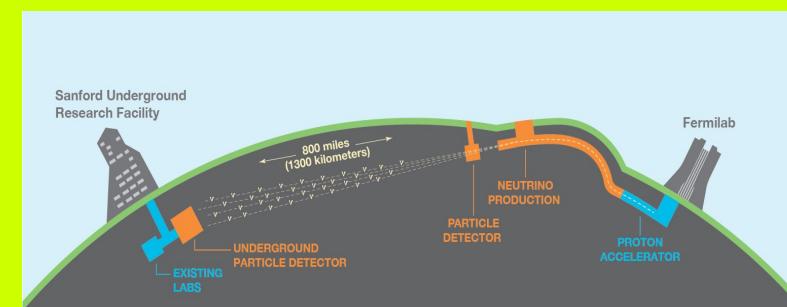
three neutrino paradigm

will not further discuss the ordering spectrum,

will focus on CP and octant determination

- CP phase
- atm octant

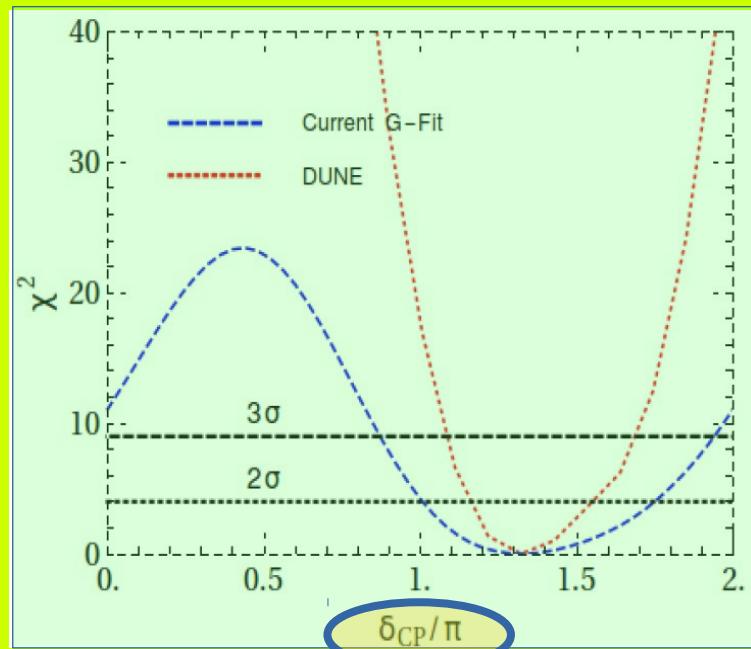
leptonic CP violation



Kim Siyeon, Jae Yu & Alan Bross talks

future CP phase

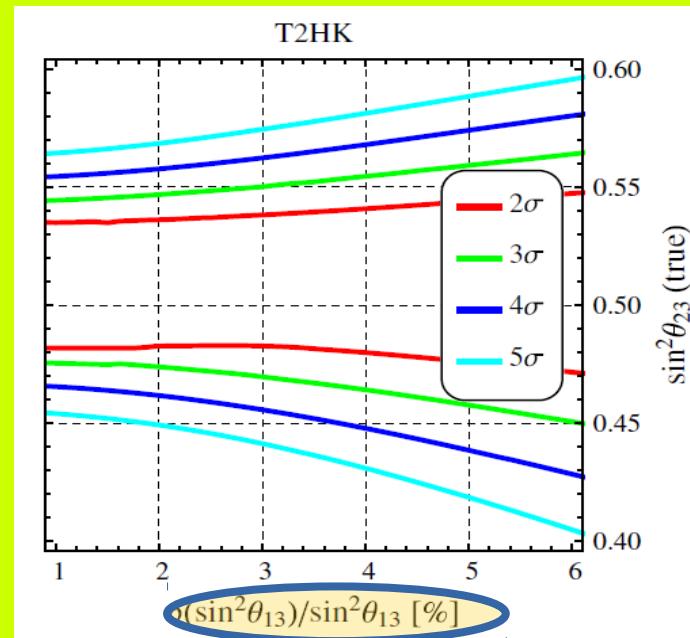
from
1811.07040



atm octant

from
Phys.Rev.D96 (2017) 011303(R)

See also
Phys.Rev. D97 (2018) 095025



2, 3, 4 and 5 σ
“octant-blind”
regions remain

what did we learn

$$\begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

Θ_{13}
CP

Harrison, Scott & Perkins 2002

systematic CP revamp

Chen et al
Phys.Lett. B753 (2016) 644-652
Phys.Rev. D94 (2016) 033002
JHEP 1807 (2018) 077
Phys.Lett. B792 (2019) 461-464
Phys.Rev. D99 (2019) 075005

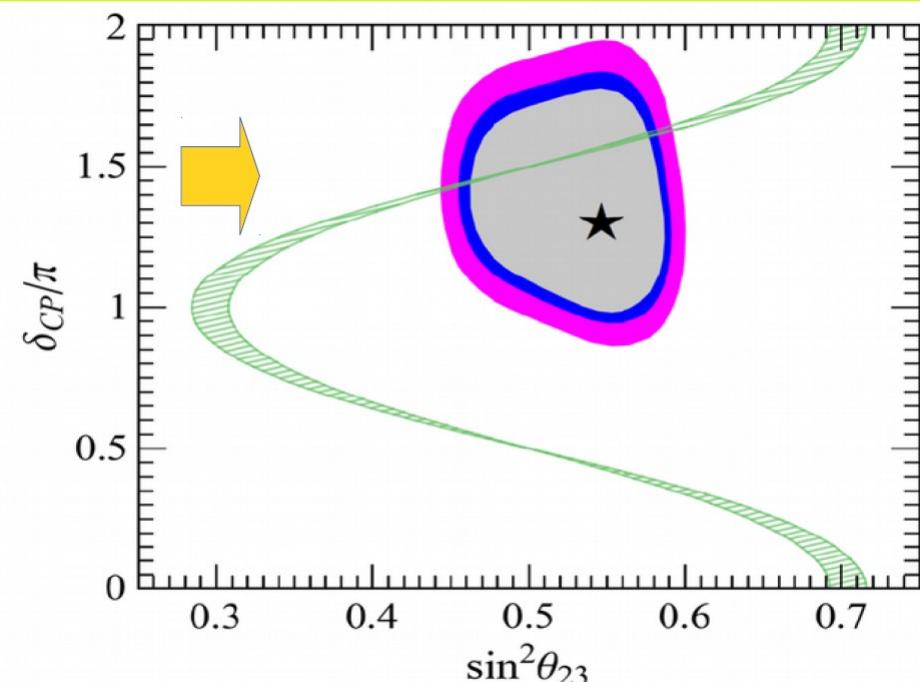
Can have other
Revamped TBM ansatze

TBM lepton mixing pattern

$$\begin{array}{|c|c|}\hline & \sin^2\theta_{12} = \frac{\cos^2\theta}{\cos^2\theta + 2}, \\ \hline & \sin^2\theta_{13} = \frac{\sin^2\theta}{3}, \\ \hline & \tan\delta_{CP} = \frac{(\cos^2\theta + 2)\cot\sigma}{5\cos^2\theta - 2}, \\ \hline & \text{PHYSICAL REVIEW D } 98, 055019 (2018) \\ \hline \end{array}$$

predicting solar

predicting CP



from Phys.Rev. D98 (2018) 055019

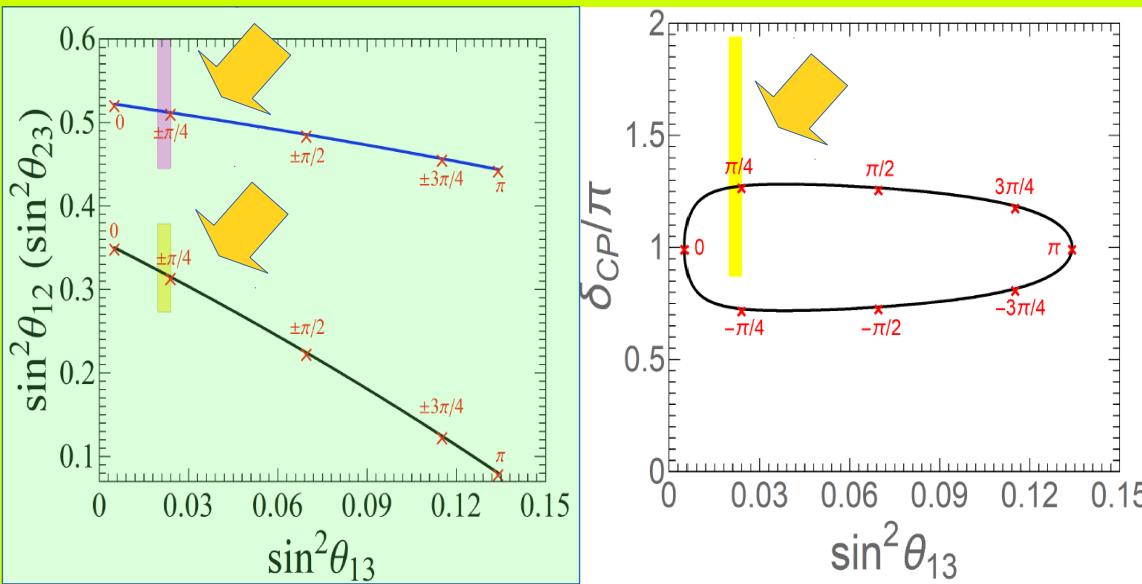
what did we learn

from 1904.05632

$$\begin{bmatrix} 1 - \frac{1}{2}\lambda^2 & -\lambda e^{i\phi} & A\lambda^3 e^{i\phi} \\ \lambda e^{-i\phi} & 1 - \frac{1}{2}\lambda^2 & -A\lambda^2 \\ 0 & A\lambda^2 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 - \frac{5\lambda^2}{2} & 2\lambda & -\lambda \\ -2\lambda + 3\lambda^2 & 1 - \frac{13\lambda^2}{2} & 3\lambda \\ \lambda + 6\lambda^2 & -3\lambda + 2\lambda^2 & 1 - 5\lambda^2 \end{bmatrix}$$

$\sin \theta_{12}^{\text{CKM}} = \lambda$ and $\sin \theta_{23}^{\text{CKM}} = A\lambda^2$, where $\lambda = 0.22453 \pm 0.00044$, $A = 0.836 \pm 0.015$



predicting solar, atm & CP from reactor angle

"soft" version of Bi-Large

Bi-Large lepton mixing pattern

Largest Q-mixing similar to smallest L-mixing
Cabibbo angle as universal seed for flavor mixing

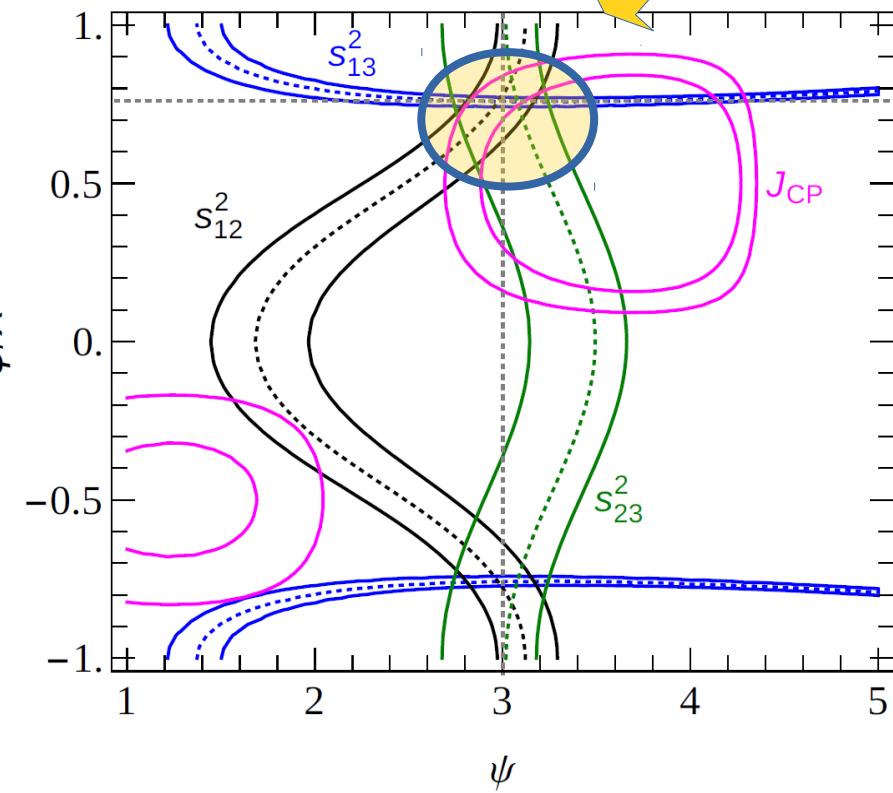
Phys.Rev. D86 (2012) 051301

Phys.Rev.D87 (2013) 053013

Phys.Lett. B748 (2015) 1-4

Phys.Lett. B792 (2019) 461-464

from 1904.05632



robustness

J.V. Phys.Lett. B199 (1987) 432-436
 Miranda & J.V. Nucl.Phys. B908 (2016) 436
 Escrihuela et al, Phys.Rev. D92 (2015) 053009

$$\begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

One parameter (1 d.o.f.)

All parameters (6 d.o.f.)

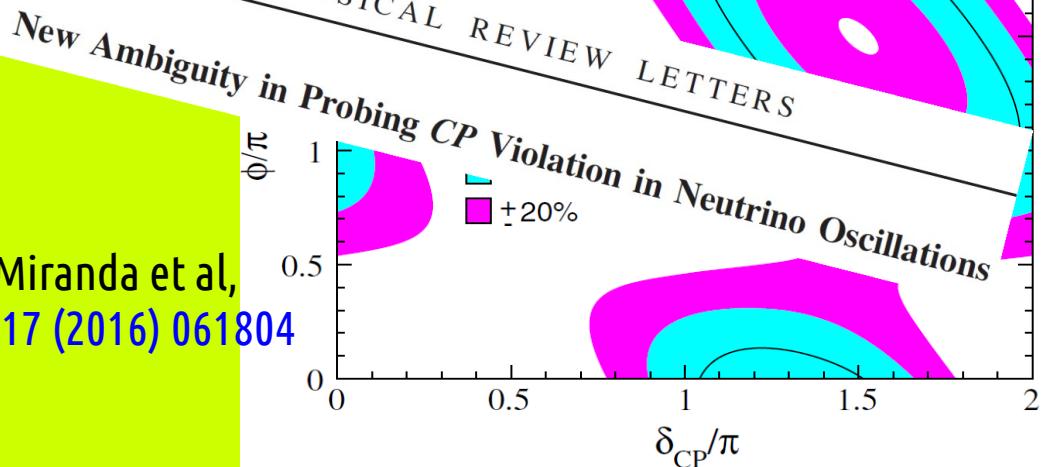
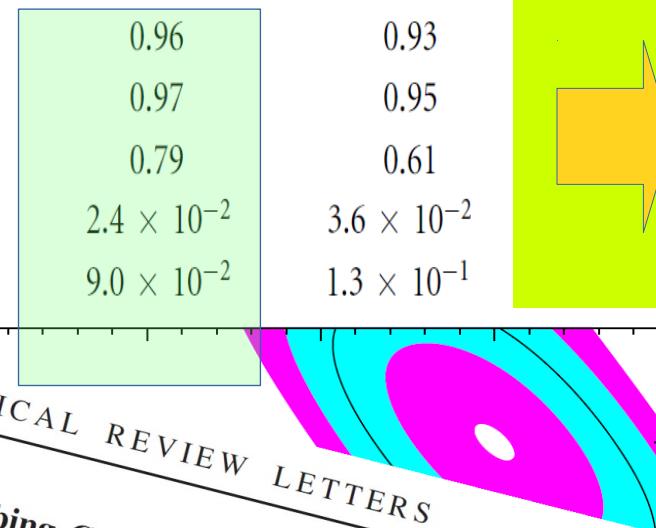
90% C.L.

3σ

90% C.L.

Neutrinos only

$\alpha_{11} >$	0.98	0.95
$\alpha_{22} >$	0.99	0.96
$\alpha_{33} >$	0.93	0.76
$ \alpha_{21} <$	1.0×10^{-2}	2.6×10^{-2}
$ \alpha_{31} ^{PRL 117, 061804 (2016)}$	10^{-2}	9.8×10^{-2}
$ \alpha_3 $		



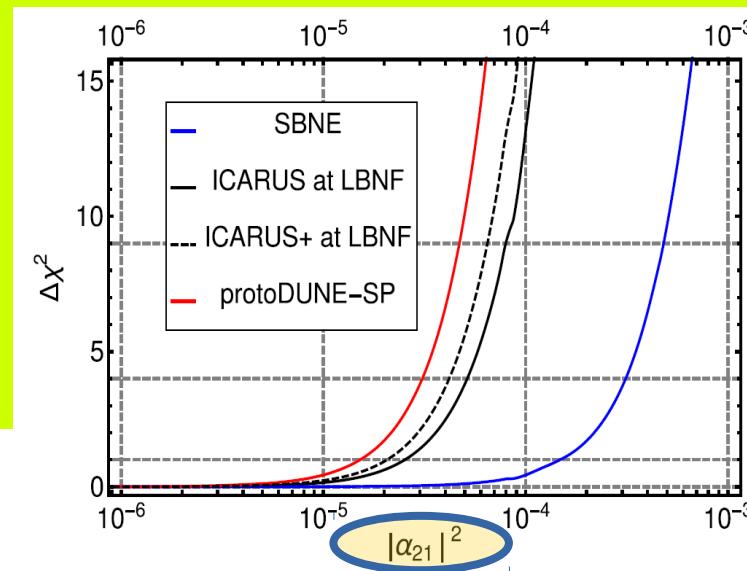
CP ambiguity Miranda et al,
 Phys.Rev.Lett. 117 (2016) 061804

unitarity test as seesaw scale probe

Shao-Feng Ge et al
 Phys.Rev. D95 (2017) 033005
 Escrihuela et al
 New J. Phys. 19 (2017) 093005

BSM window

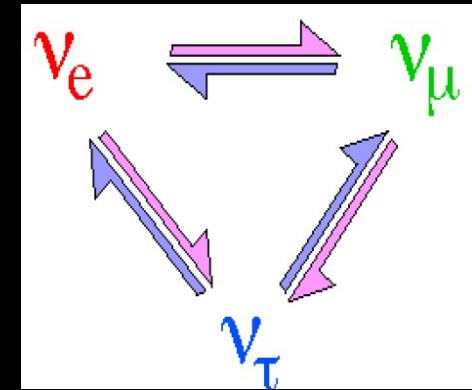
PRD97 (2018) 095026



nsi

Coloma, Huber et al, Miranda et al,
 de Gouvea et al, Goswami et al,
 Kopp et al, Antusch et al,
 Fernandez, Lopez Pavon,
 Martinez-Soler, Minakata, ...

OSCillation legacy



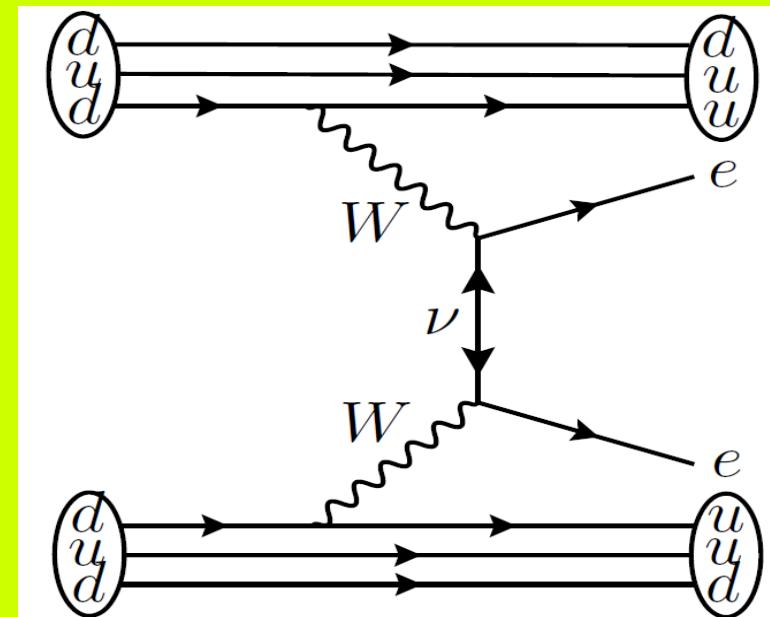
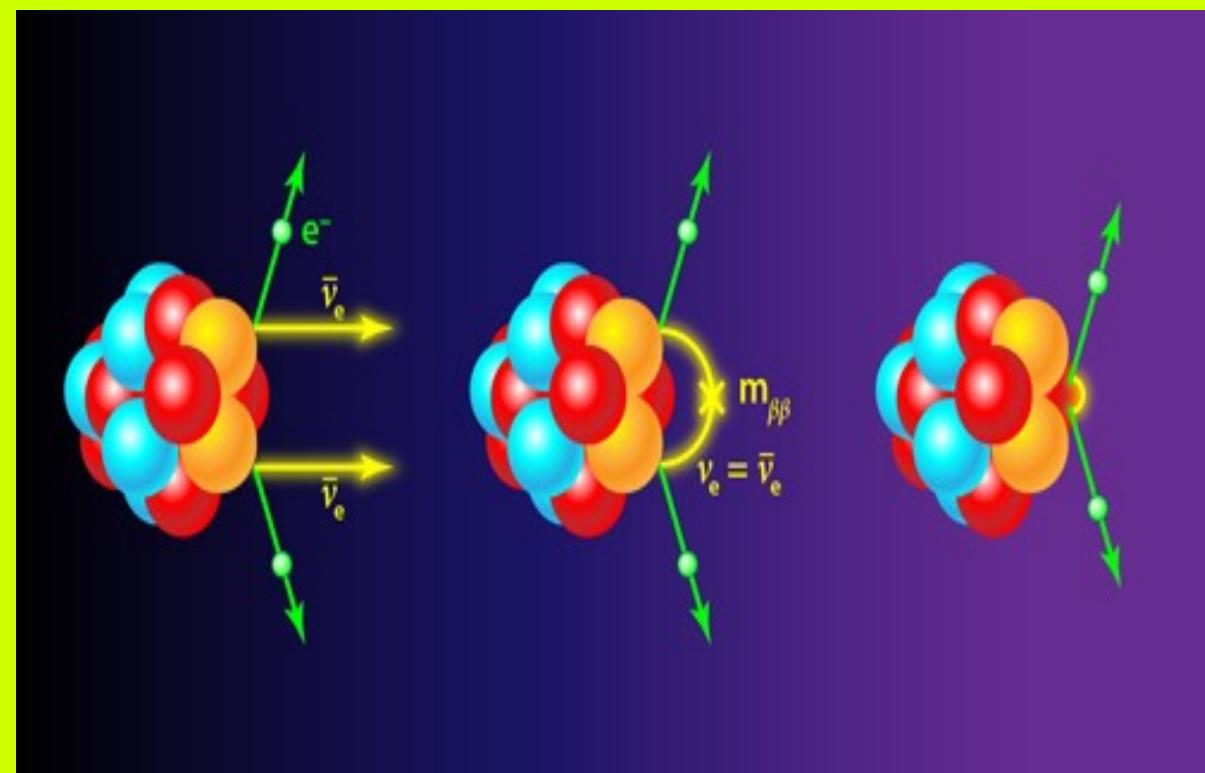
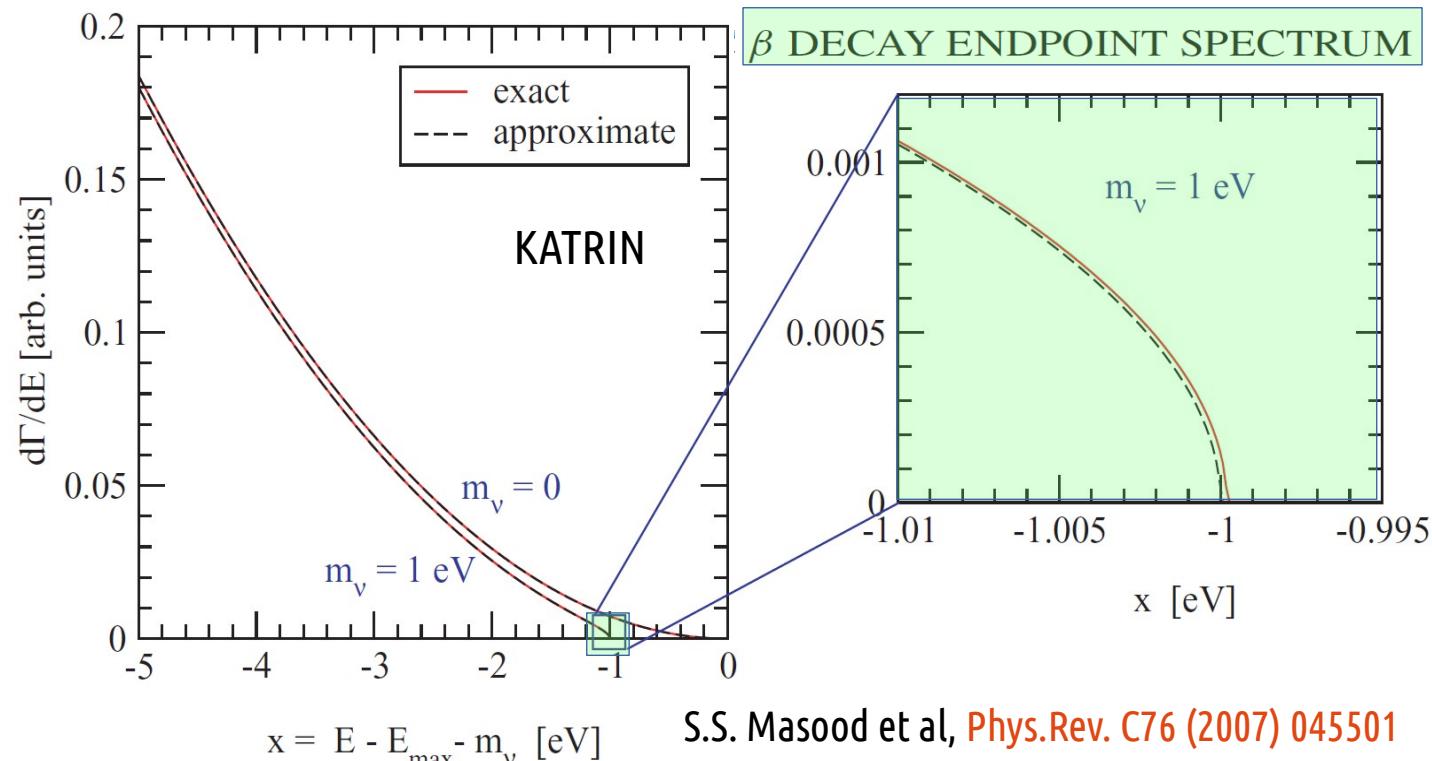
Oscillations bring neutrinos to the center of the stage

addressing the dynamical origin of small neutrino mass
touches the heart of the EW theory

besides neutrino mass dynamics, there are other issues in particle physics & cosmology for which neutrinos may provide key input

e.g. flavor, EW breaking, unification, DM ...

nuclear physics as probe of neutrino mass scale



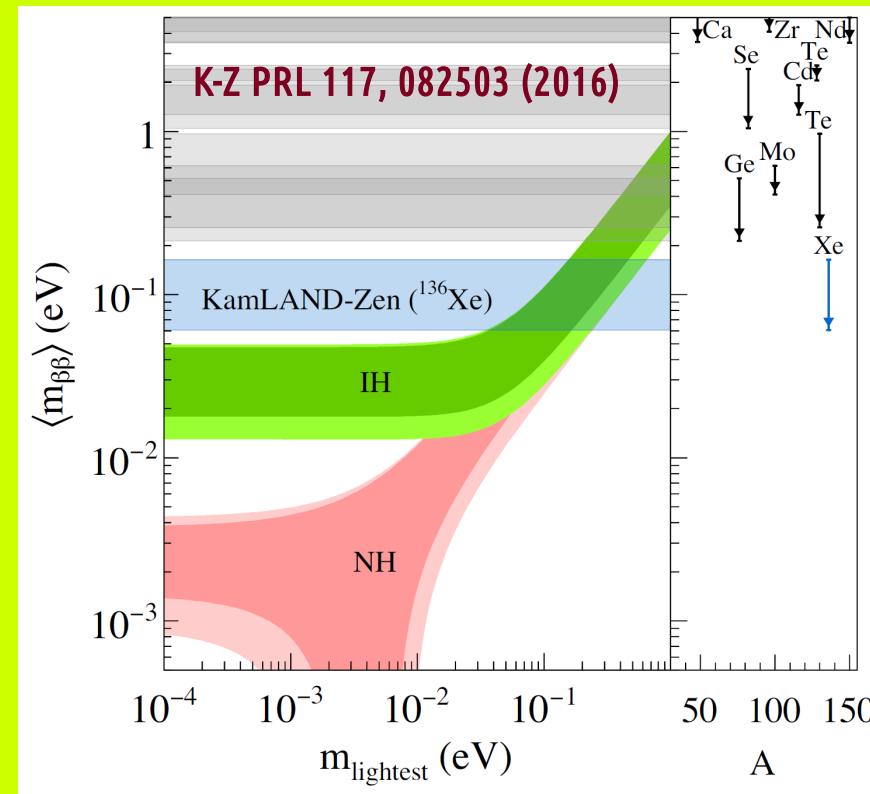
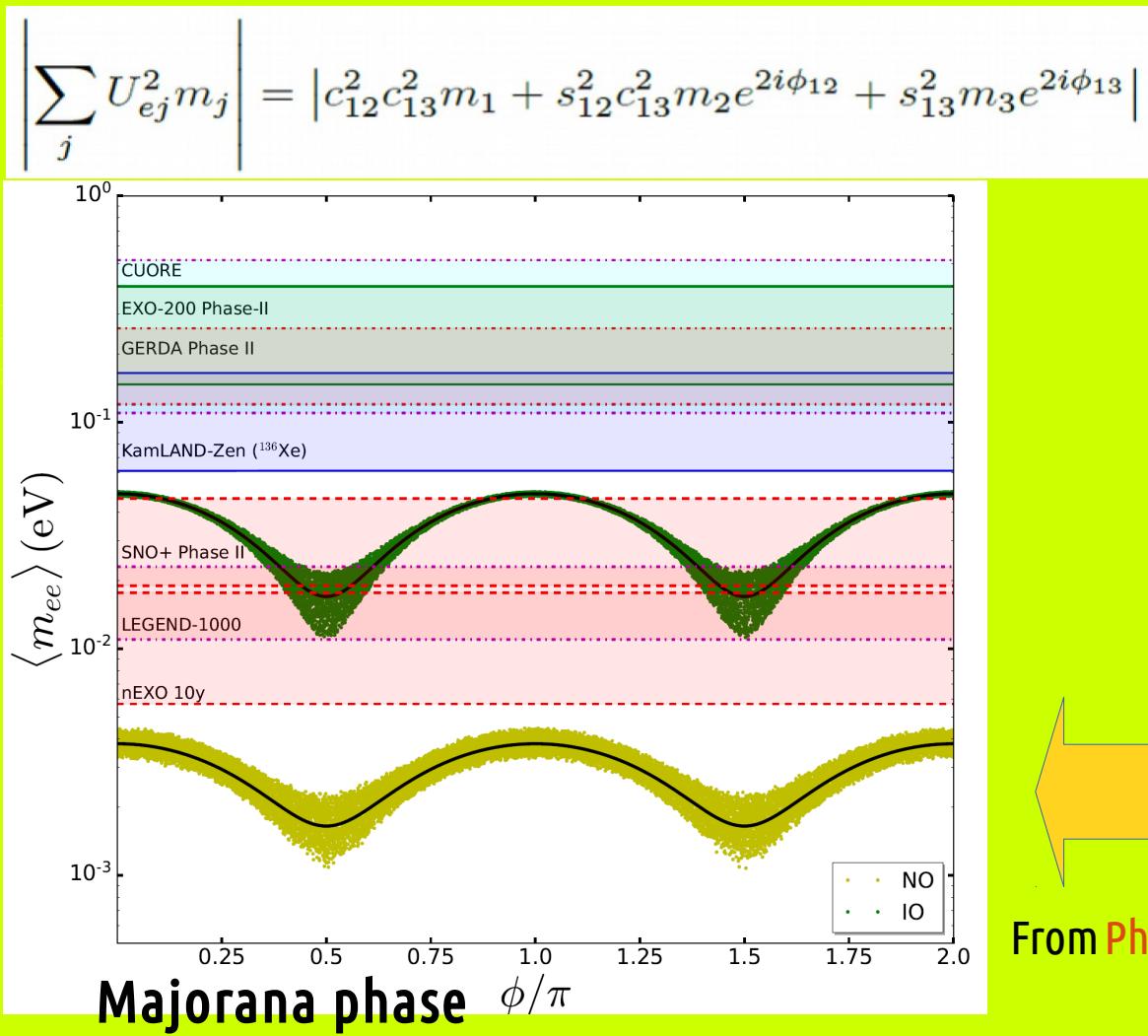
ABSOLUTE MASS & MAJORANA PHASES

neutrinoless double beta decay

symmetric parametrization of lepton mixing matrix

Schechter & JV PRD22 (1980) 2227

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



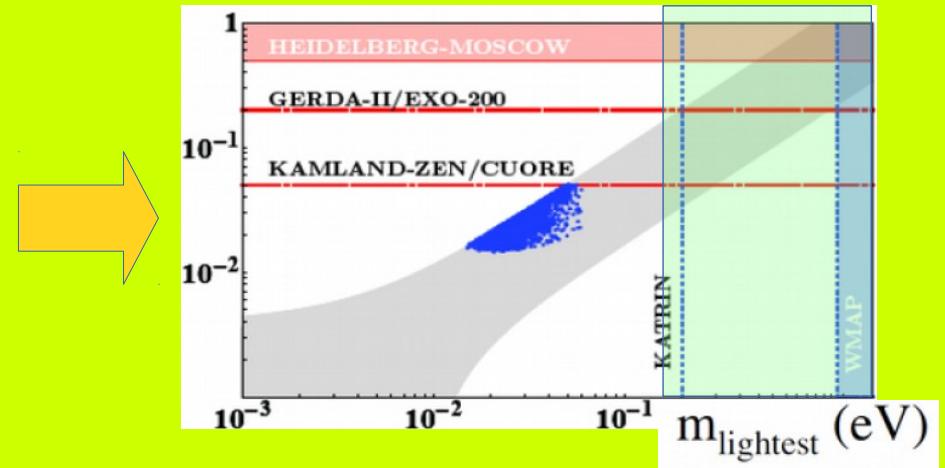
EXO: 1906.02723 CUORE:1605.02889
nEXO, LEGEND (nGERDA/Majorana) ...

if one neutrino is massless

From Phys.Lett. B790 (2019) 303-307

neutrinoless doublebeta decay

flavor sensitivity



lower bounds even for normal ordering

Dorame et al

NPB861 (2012) 259-270

Dorame et al

PhysRevD.86.056001

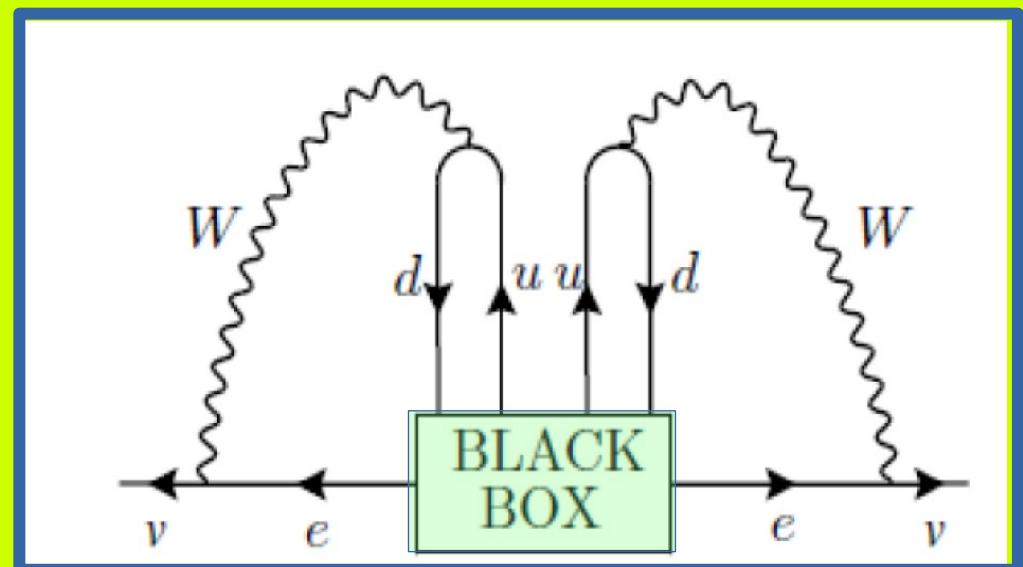
King et al

Phys. Lett. B 724 (2013) 68

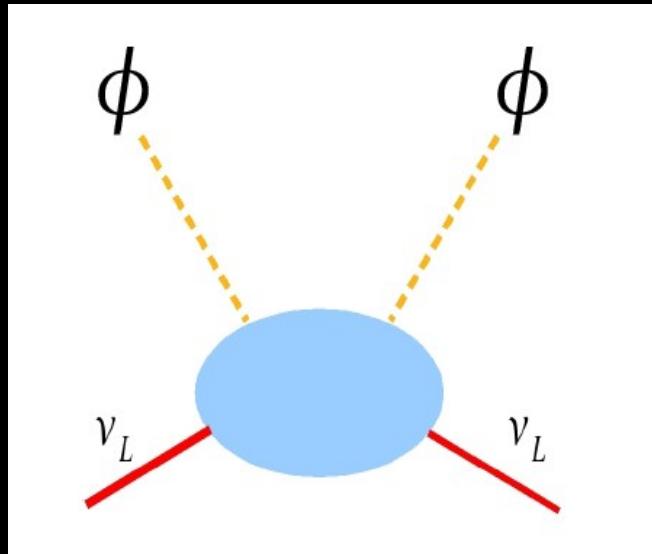
Significance

Schechter, Valle 82

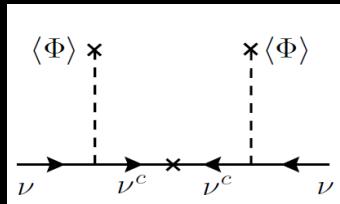
Lindner et al JHEP 1106 (2011) 091



Origin of neutrino mass

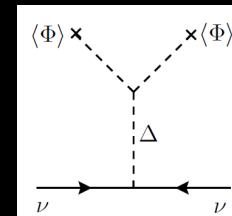


coefficient
mechanism
scale
flavor structure



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

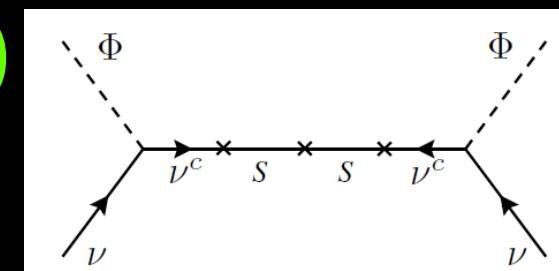
seesaw

$$v_3 v_1 \sim v_2^2$$

bottom up $3 \times 2_L \times 1$ seesaw \rightarrow any # of singlet R's: m

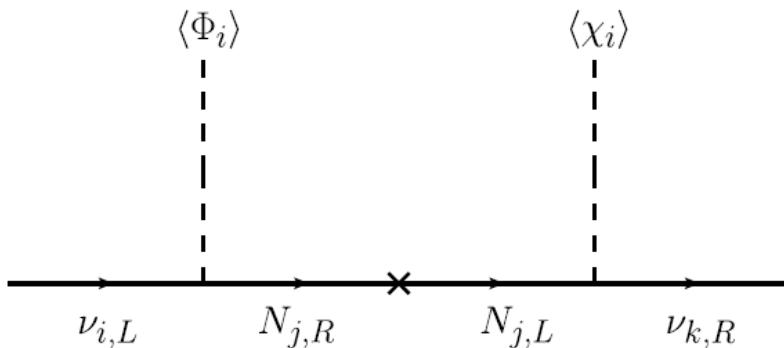
\Rightarrow MISSING PARTNER SEESAW (3,2)
(3,1) "dark"-seesaw

\Rightarrow LOW-SCALE SEESAW (3,6)
Mohapatra-Valle 86
Akhmedov et al PRD53 (1996) 2752
Malinsky et al PRL95(2005)161801
Bazzocchi et al, PRD81 (2010) 051701



multi-family seesaw \Rightarrow oscillation description

Seesawing a la Dirac



type1

Phys.Lett. B761 (2016) 431-436

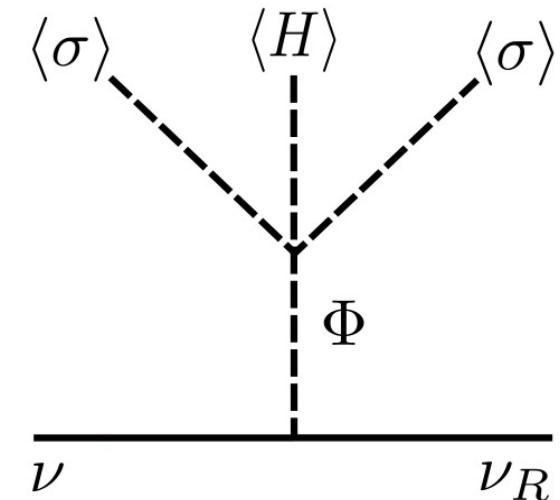
Phys.Lett. B767 (2017) 209-213



**Symmetry protects
small neutrino mass**

Phys.Rev. D98 (2018) 035009

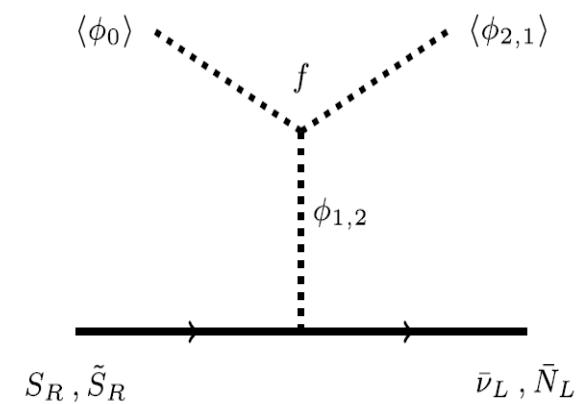
Phys.Lett. B781 (2018) 122-128



type2

Phys.Lett. B762 (2016) 162-165

Phys.Rev. D94 (2016) 033012



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

Phys.Lett. B755 (2016) 363-366

radiative neutrino mass

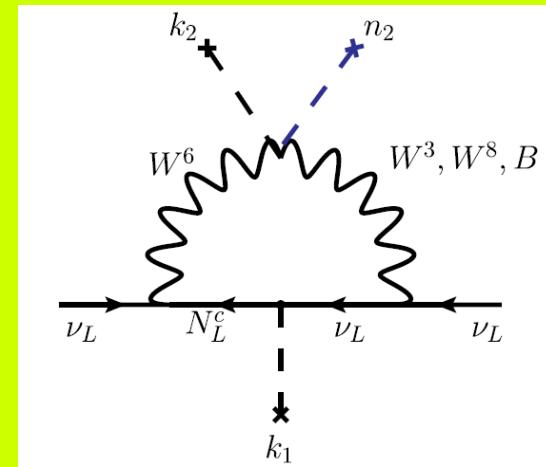
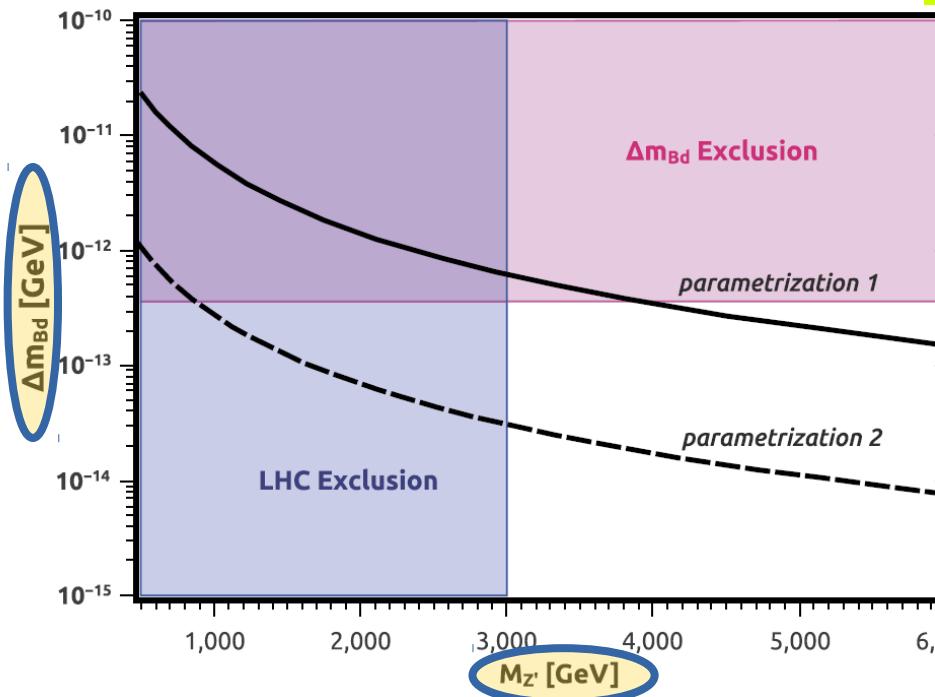
3 x 3_L x 1 motivation

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

- why 3 families
- tree-level quark FCNC
- gauge mediated calculable neutrino mass

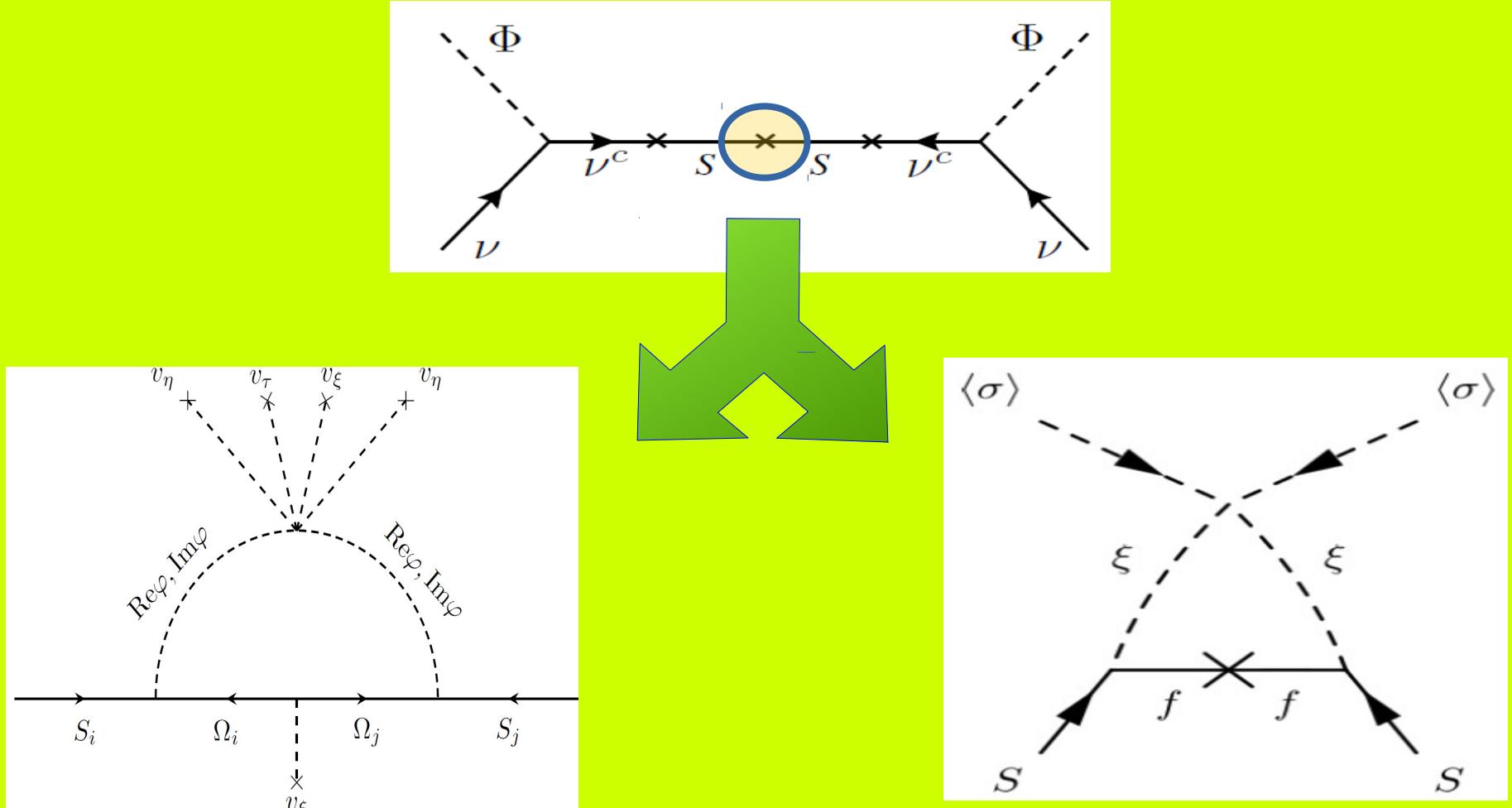
high energy vs high intensity

F.S. Queiroz et al. / Physics Letters B 763 (2016) 269–274



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

double protected low scale seesaw



radiative inverse/linear seesaw

Cárcamo Hernández et al JHEP 1902 (2019) 065

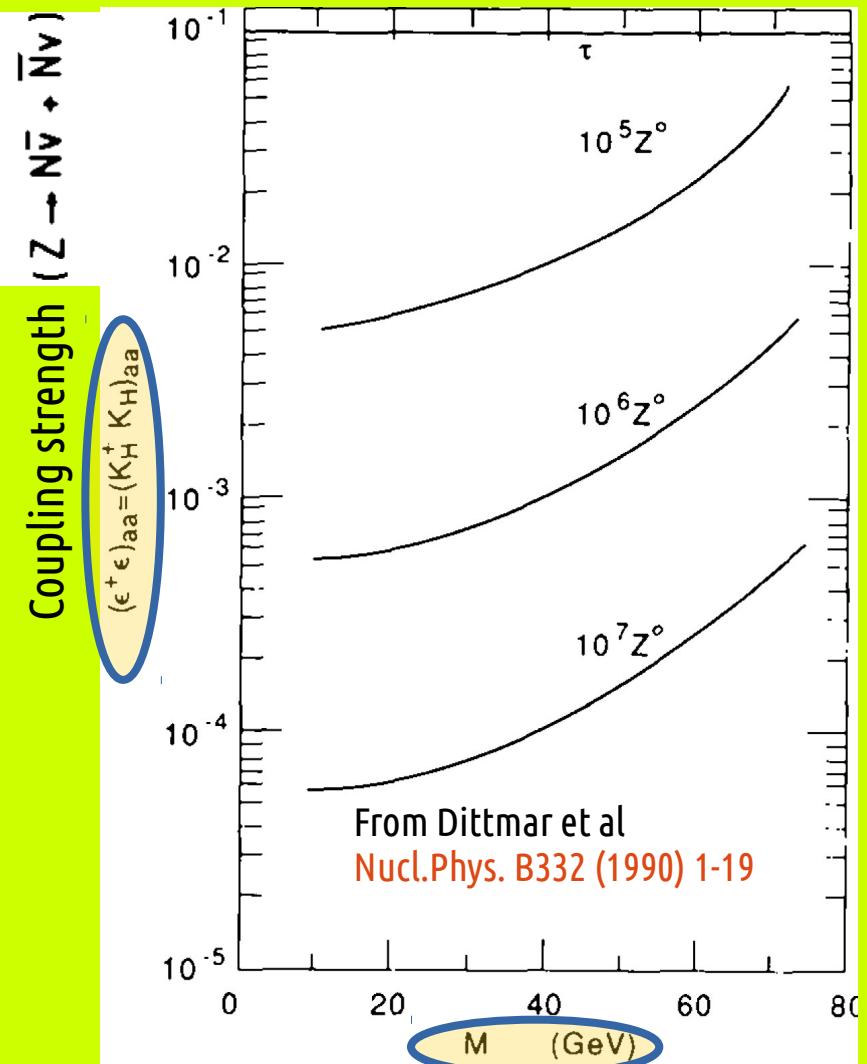
See also Bazzocchi et al 0907.1262

Ma 0904.4450

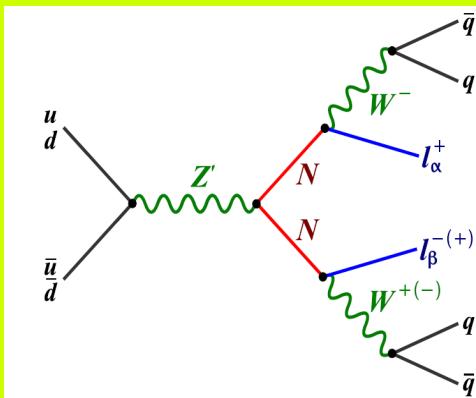
scotogenic inverse seesaw

From arXiv:1907.07728

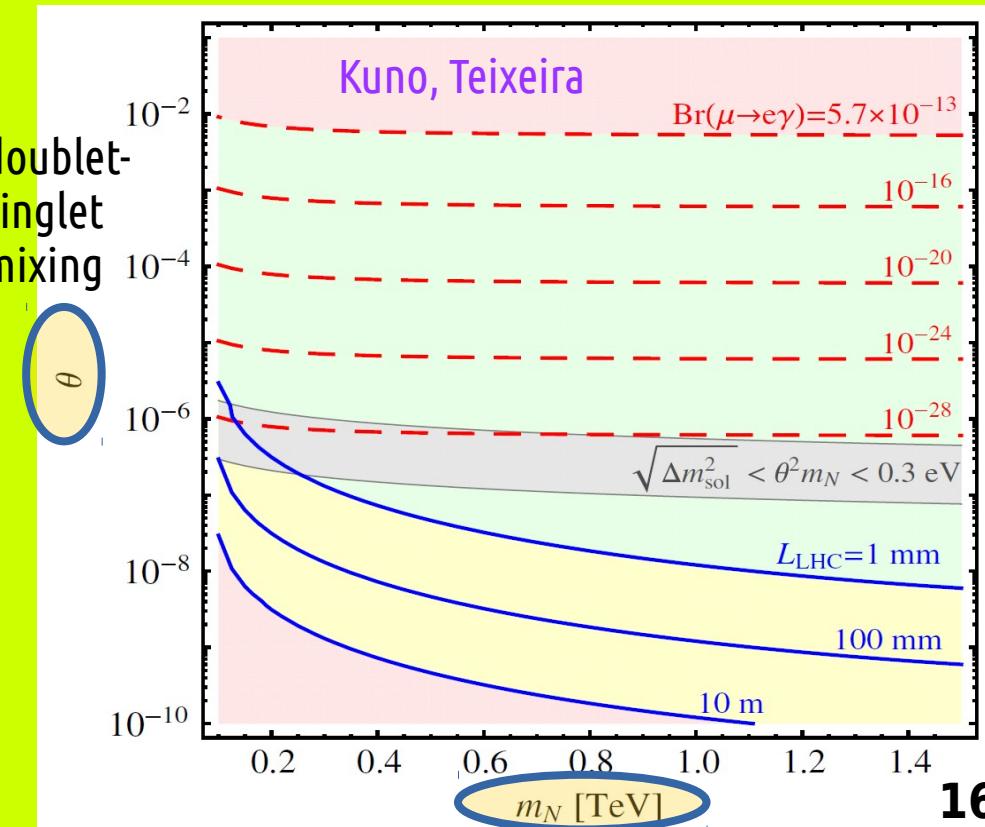
Baldes et al 1304.6162



mediator searches charged lepton flavor violation at high energies



From Phys.Rev. D89 (2014) 051302
Also full LR Phys.Rev. D86 (2012) 055006





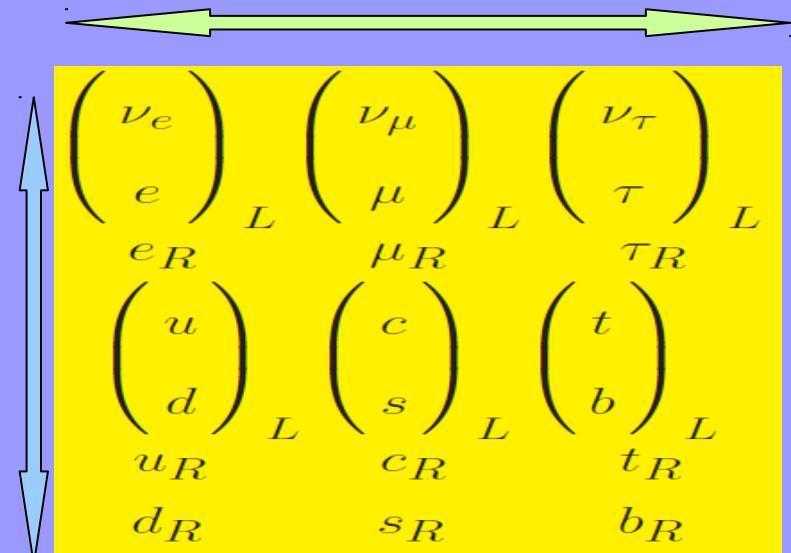
SM lacks an organizing principle to understand flavor

Simplest flavor symmetry

A4

$$\sin^2 \theta_{23} = 0.5$$

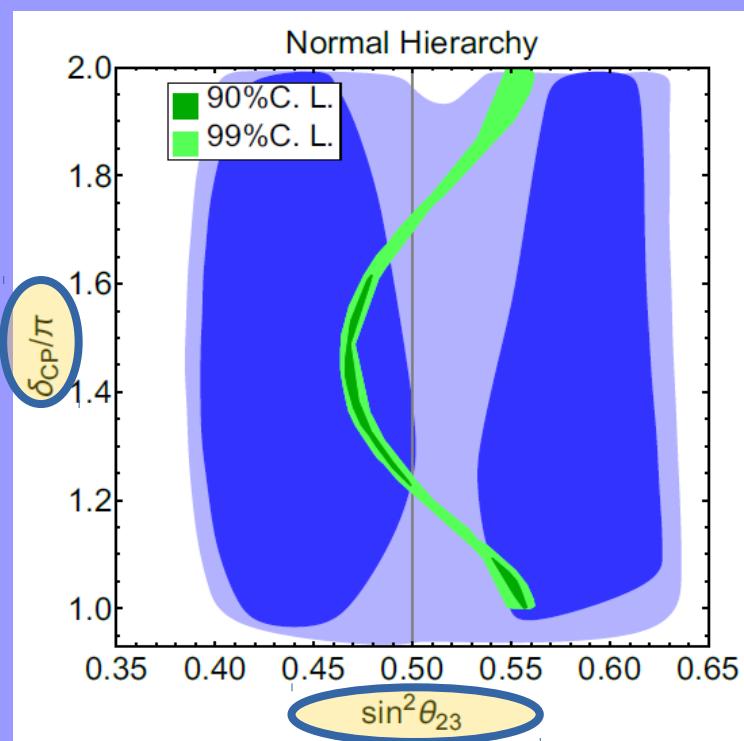
$$\sin^2 \theta_{13} = 0$$



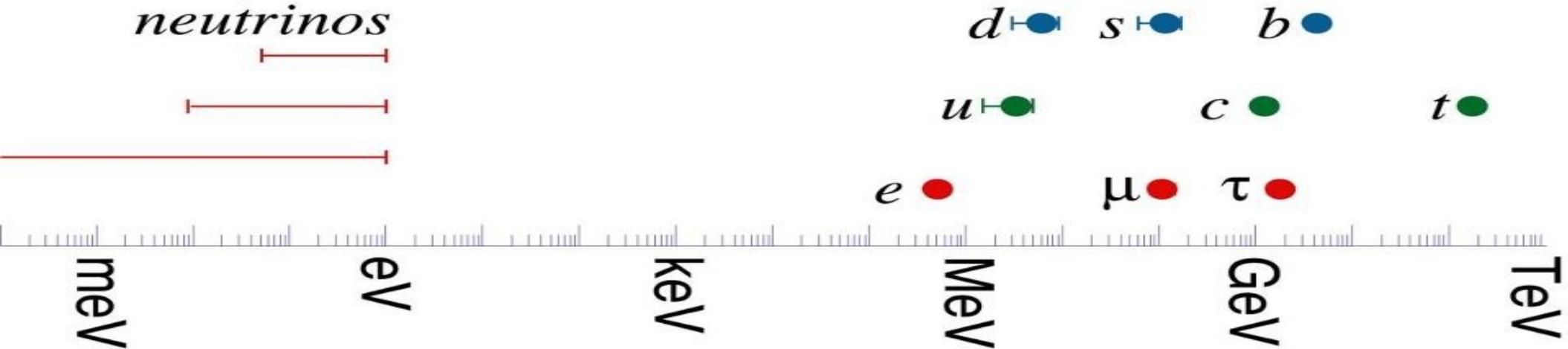
Babu-Ma-Valle PLB552 (2003) 207
 Hirsch et al PRD69 (2004) 093006

still good starting point ... predictive revamping
 Morisi et al, Phys.Rev. D88 (2013) 016003

Constrained global fit
 Phys.Lett. B774 (2017) 179-182



probed now
 Improvement at LBL
 experiments, e.g. DUNE
 cosmology



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

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

Warped SM With flavor

Constrained global fitting

Chen et al
JHEP01(2016)007

mass hierarchies from geometry

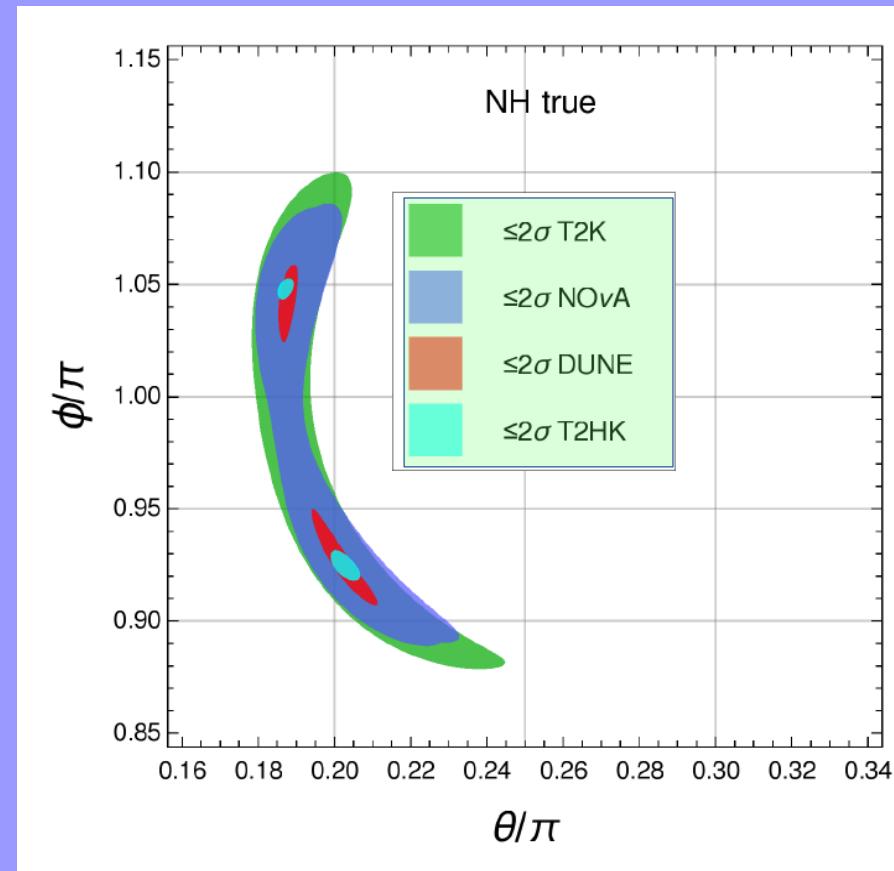
→ angles related by symmetry

$$\sin^2 \theta_{12} = \frac{1}{2 - \sin 2\theta_v \cos \phi_v}$$

$$\sin^2 \theta_{13} = \frac{1}{3} (1 + \sin 2\theta_v \cos \phi_v)$$

$$\sin^2 \theta_{23} = \frac{1 - \sin 2\theta_v \sin(\pi/6 - \phi_v)}{2 - \sin 2\theta_v \cos \phi_v}$$

$$J_{CP} = -\frac{1}{6\sqrt{3}} \cos 2\theta_v$$



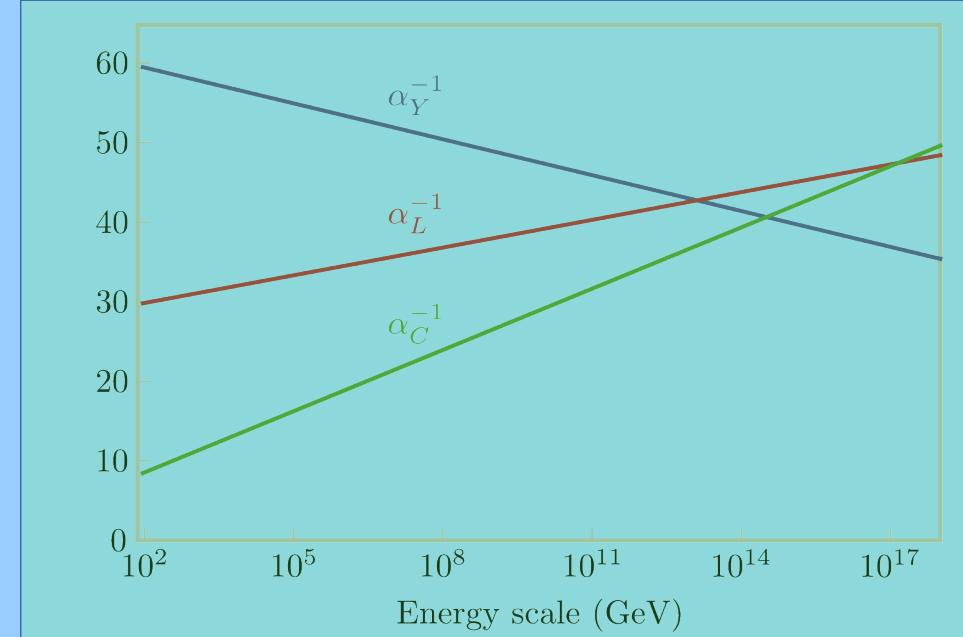
Predictions for LBL experiments

Phys. Rev. D95 (2017) 095030

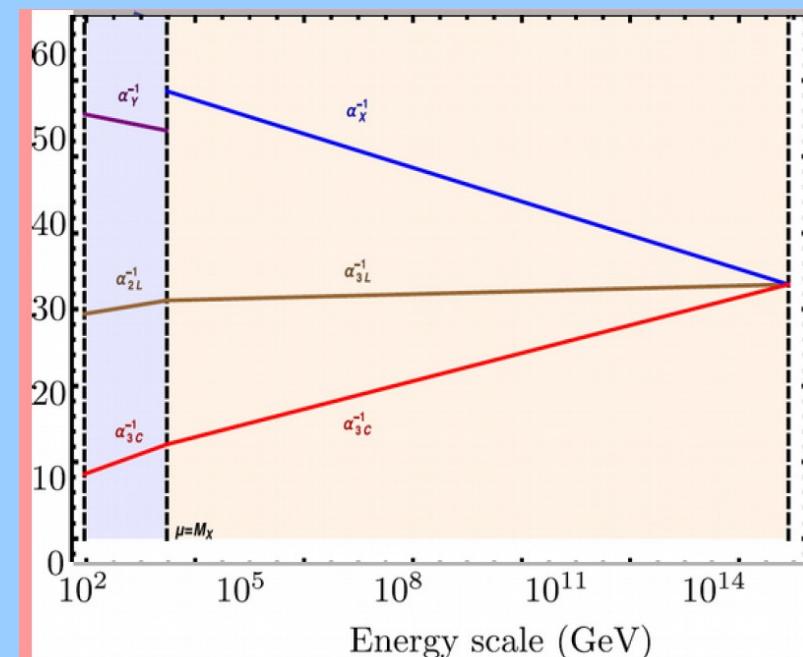
Phys. Lett. B771 (2017) 524

Standard model

although unification is missed ...
the trend is there ...



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



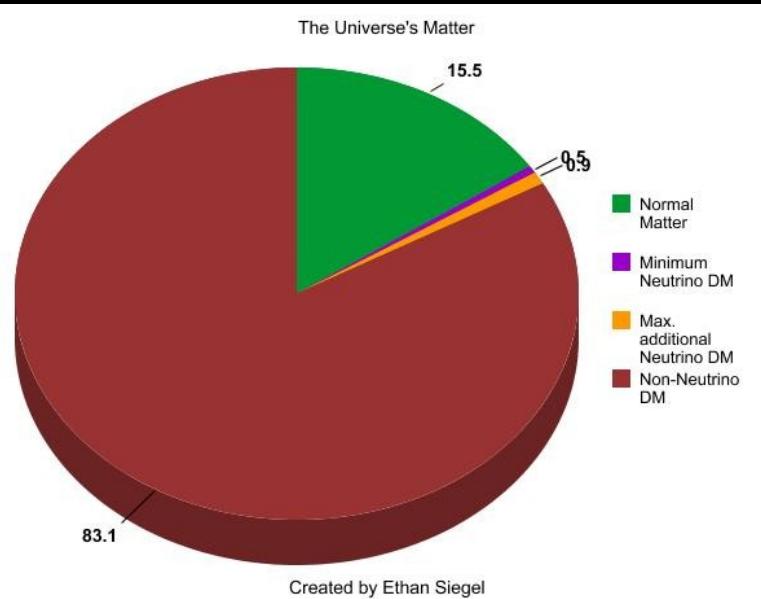
neutrinos & unification

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

E(6) F-theory GUT

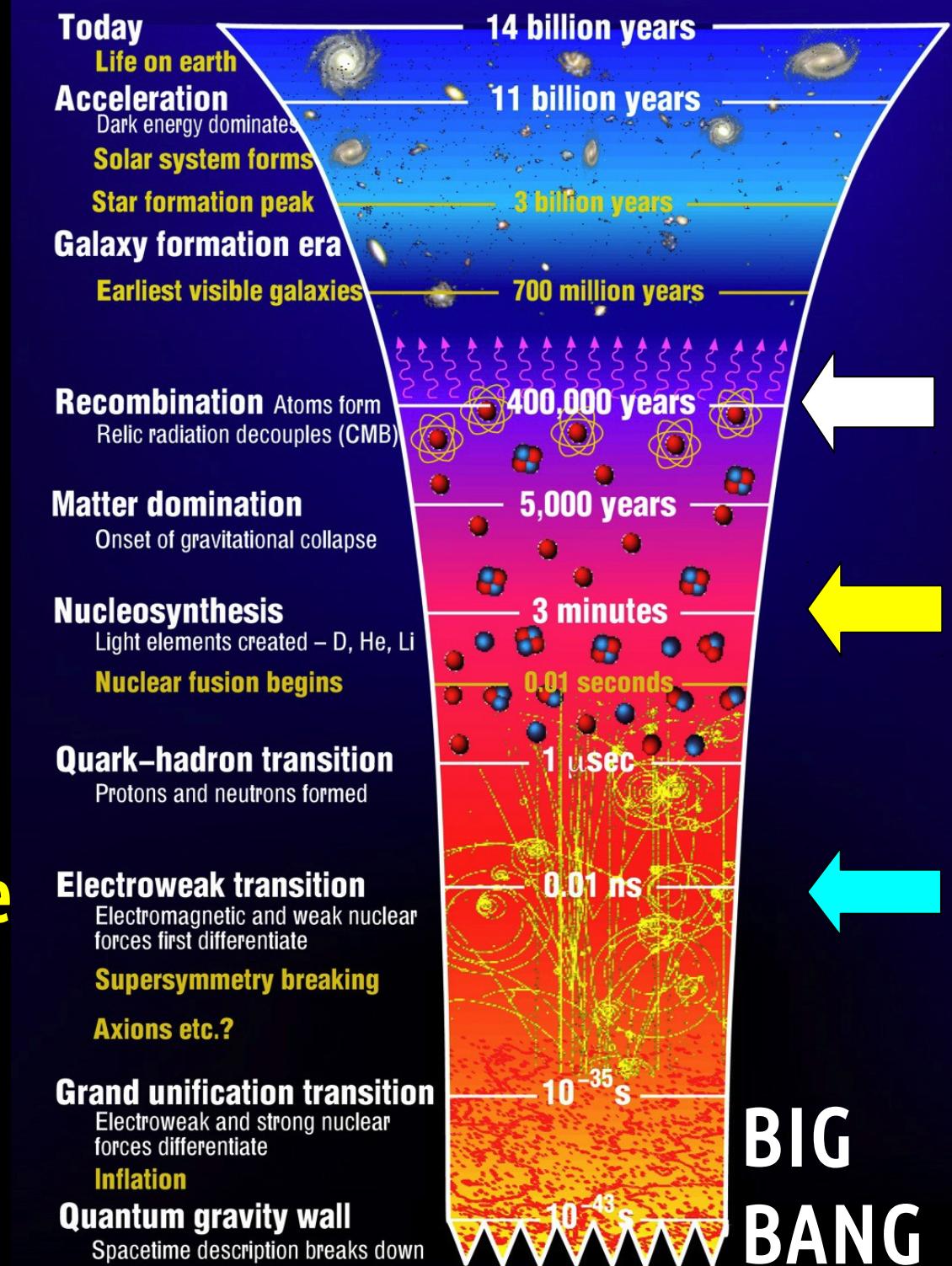
Boucenna et al Phys. Rev. D 91, 031702 (2015)

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



need for dark matter

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



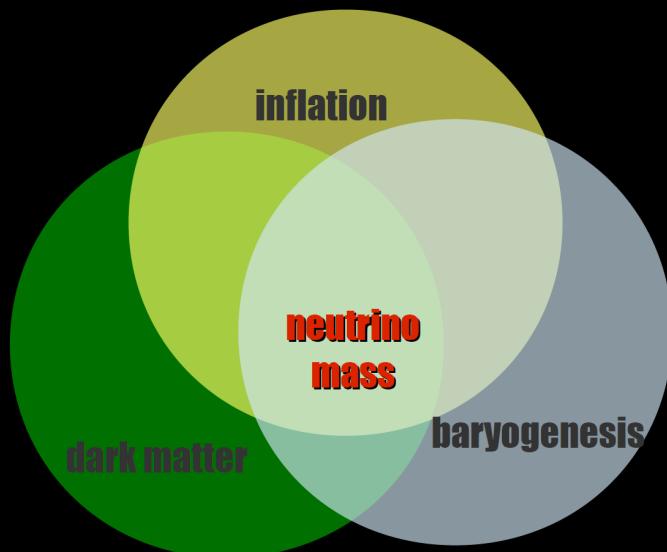
opportunities

- › bright future for oscillation studies, non-unitarity-nsi
- › neutrinoless doublebeta decay, **coherent scattering**
- › high intensity & also high energies, e.g. LHC **expt**
- › probe for mediators via CLFV : possible LHC discovery

- › neutrinos may shed light on flavor & on unification
- › **final dream** : unify forces & families

th

"emergent cosmology"



THANKS!

Back-ups