

# Neutrino mass & new physics

José W F Valle



<https://www.facebook.com/ific.ahep/>

ISAPP 2017 Arenzano school in Neutrino Physics

1

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
 & \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \\
 & \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{M^2}{g^2} + \\
 & \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+) - ig s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + \\
 & \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2 A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] - \\
 & \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4 H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] - \\
 & \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2} ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2} ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}^\lambda (\gamma \partial + m_u^\lambda) u^\lambda - 
 \end{aligned}$$



3

$$\begin{aligned}
 & \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
 & \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (d_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \\
 & \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - 
 \end{aligned}$$

4

$$\begin{aligned}
 & \frac{g}{2} \frac{m_e^\lambda}{M} [H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_e^\lambda}{M} H(\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H(\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_e^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - 
 \end{aligned}$$

5

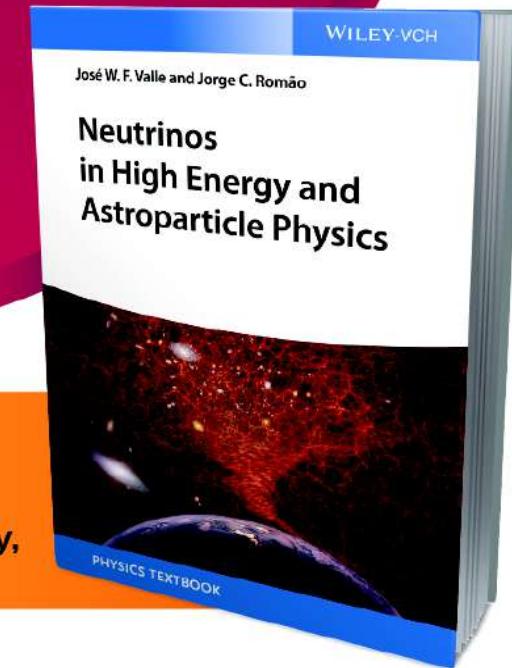
$$\begin{aligned}
 & \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + X^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
 & \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + ig c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^-) + ig s_w W_\mu^- (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
 & ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

# Neutrinos in High Energy and Astroparticle Physics

*Jose Wagner Furtado Valle,  
Jorge Romao*

ISBN: 978-3-527-41197-9  
448 pages  
February 2015

A self-contained modern advanced textbook on the role of neutrinos in astrophysics and cosmology, and high energy physics



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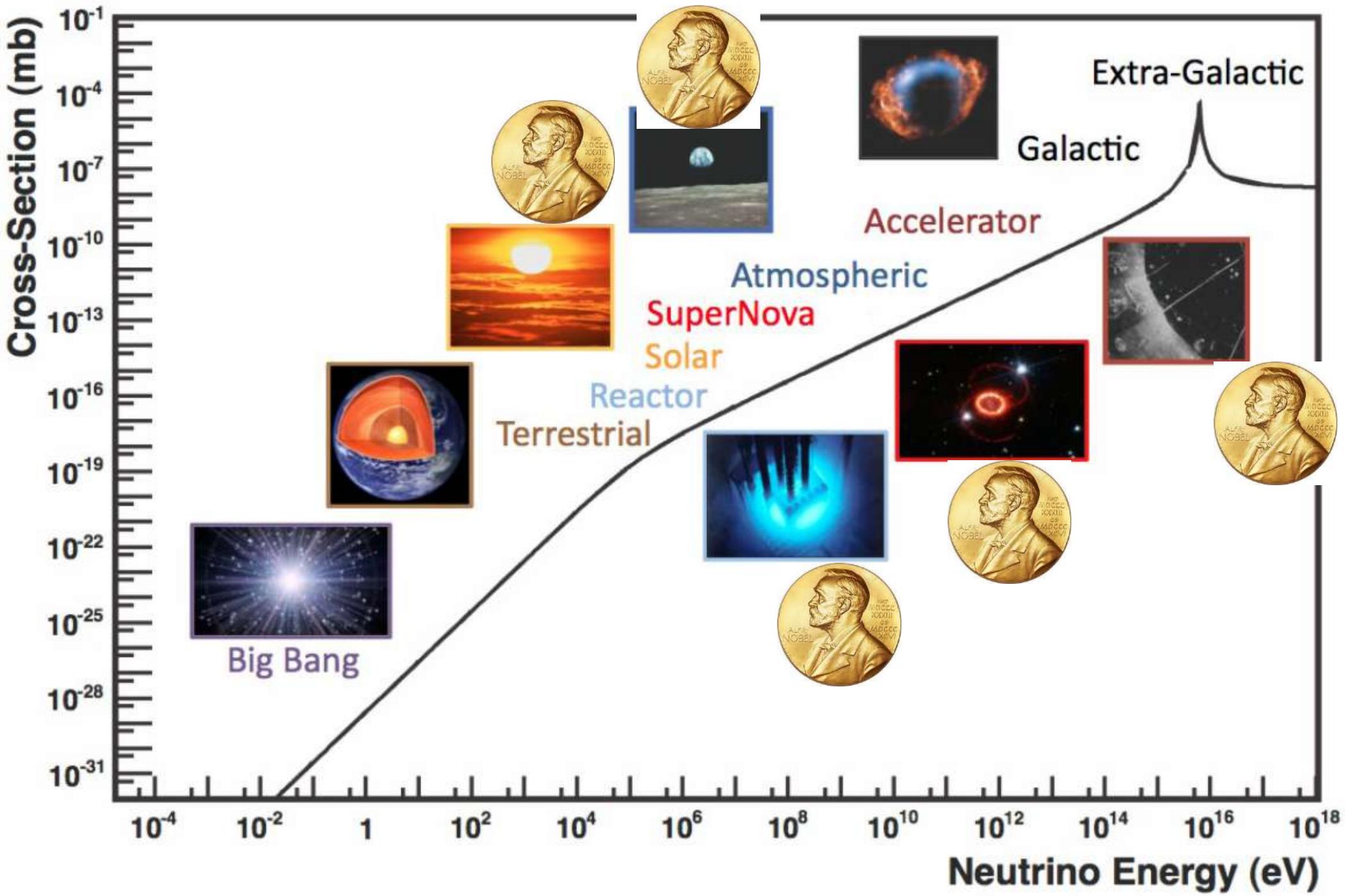
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# lecture 1

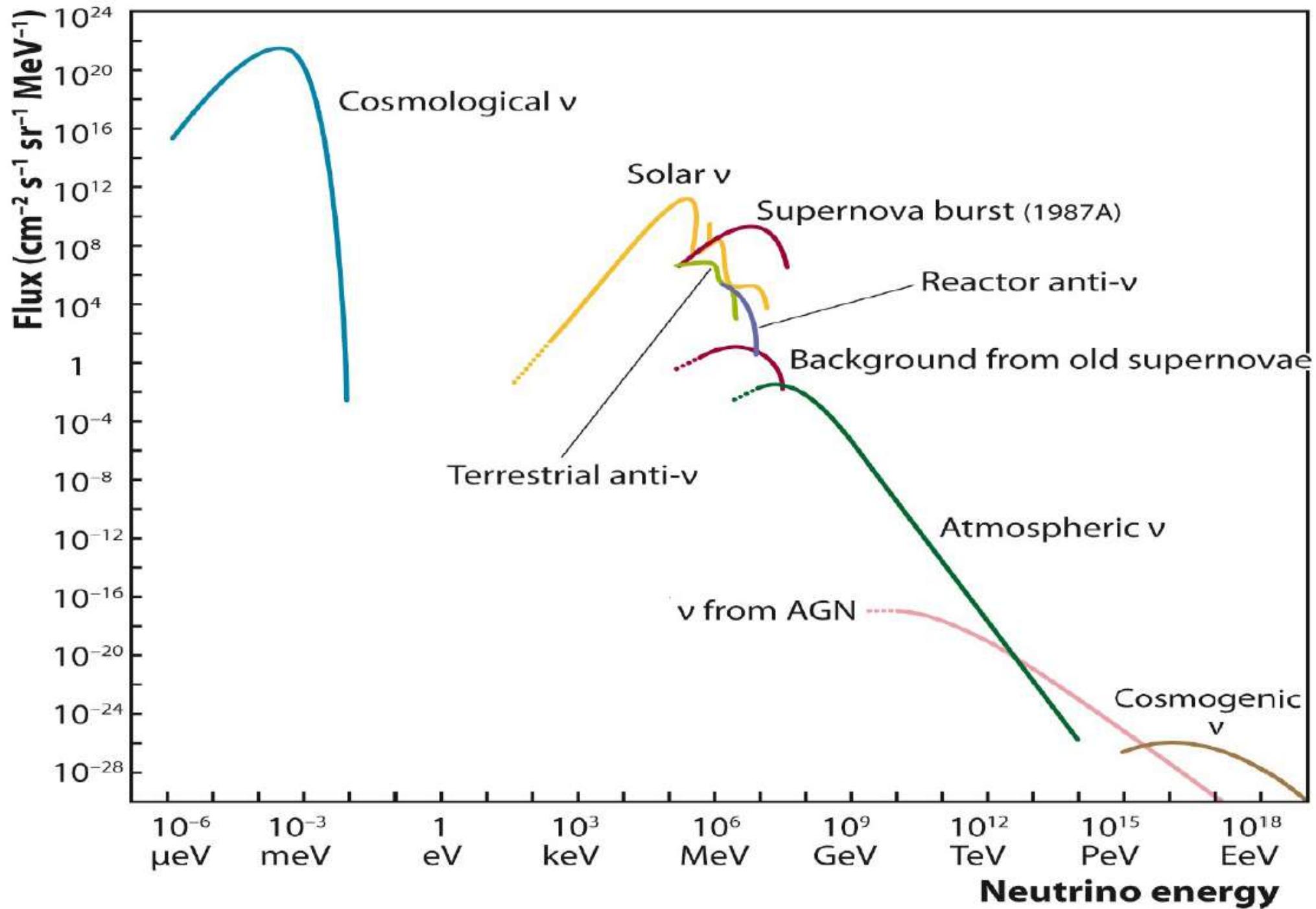
# the data

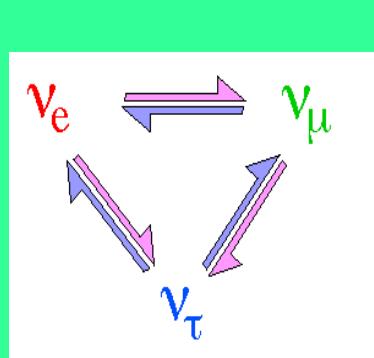
- Neutrino oscillations
- experimental status
- Atmospheric octant, CP violation & mass ordering
- Short & long-term prospects
- theoretical predictions
- Robustness and non-unitarity or NSI
- Beta & double beta decay
- Current experimental status
- Short & long-term prospects & absolute neutrino mass
- Theoretical significance of neutrinoless  $\beta\beta$  decay: the black box

# neutrino sources & cross sections



# neutrino sources & fluxes



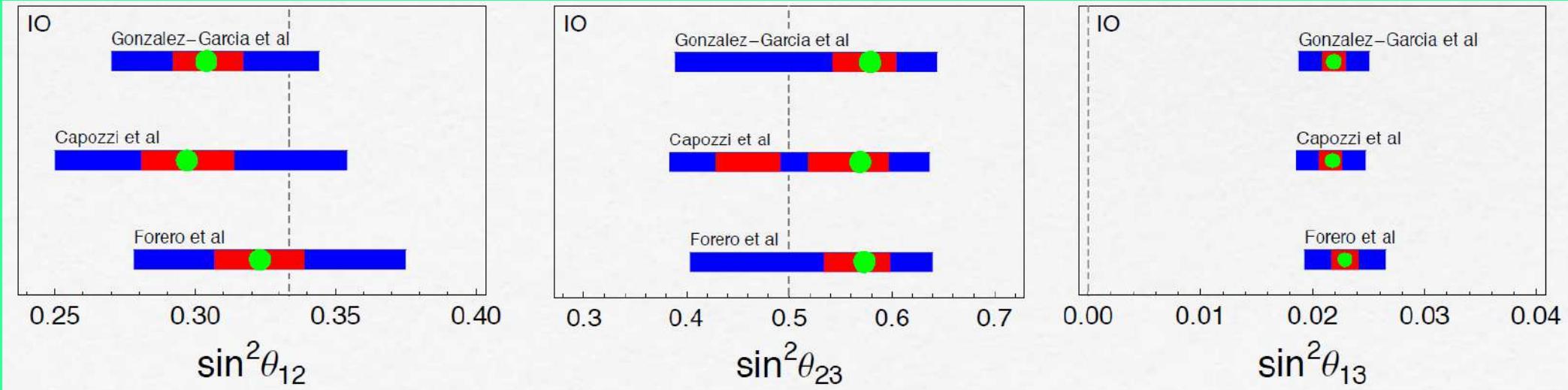


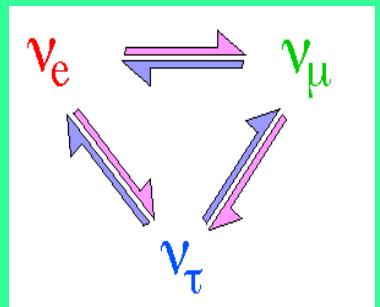
# neutrino oscillations

Why large mixing?

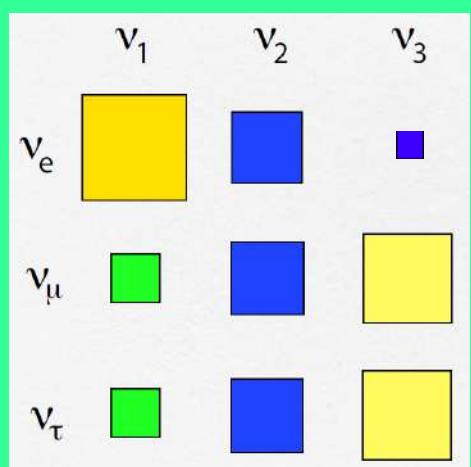
maximal CPV?

Which mass ordering?

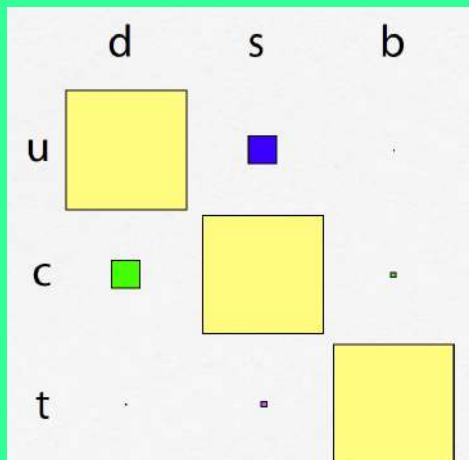




# neutrino oscillations



vs



Phys.Rev. D86 (2012) 051301  
Phys.Lett. B748 (2015) 1-4

## CP predictions

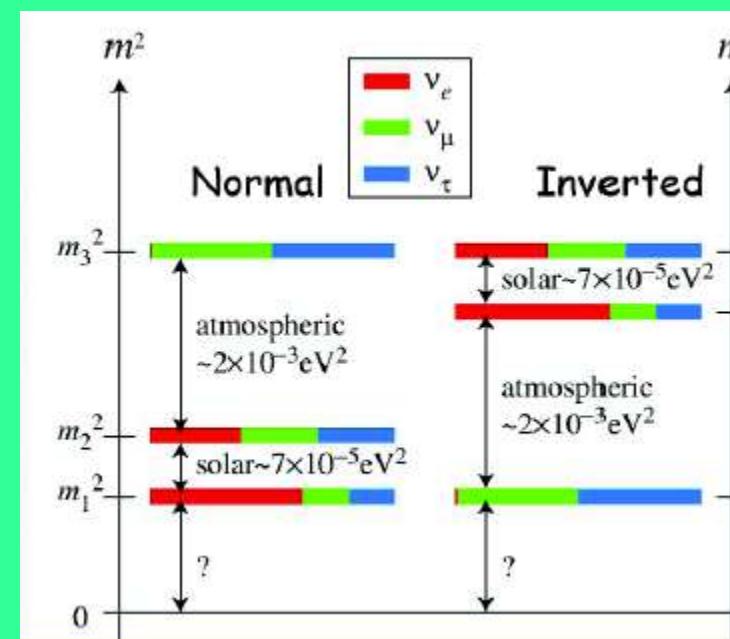
[http://dx.doi.org/10.1007/JHEP01\(2016\)007](http://dx.doi.org/10.1007/JHEP01(2016)007)

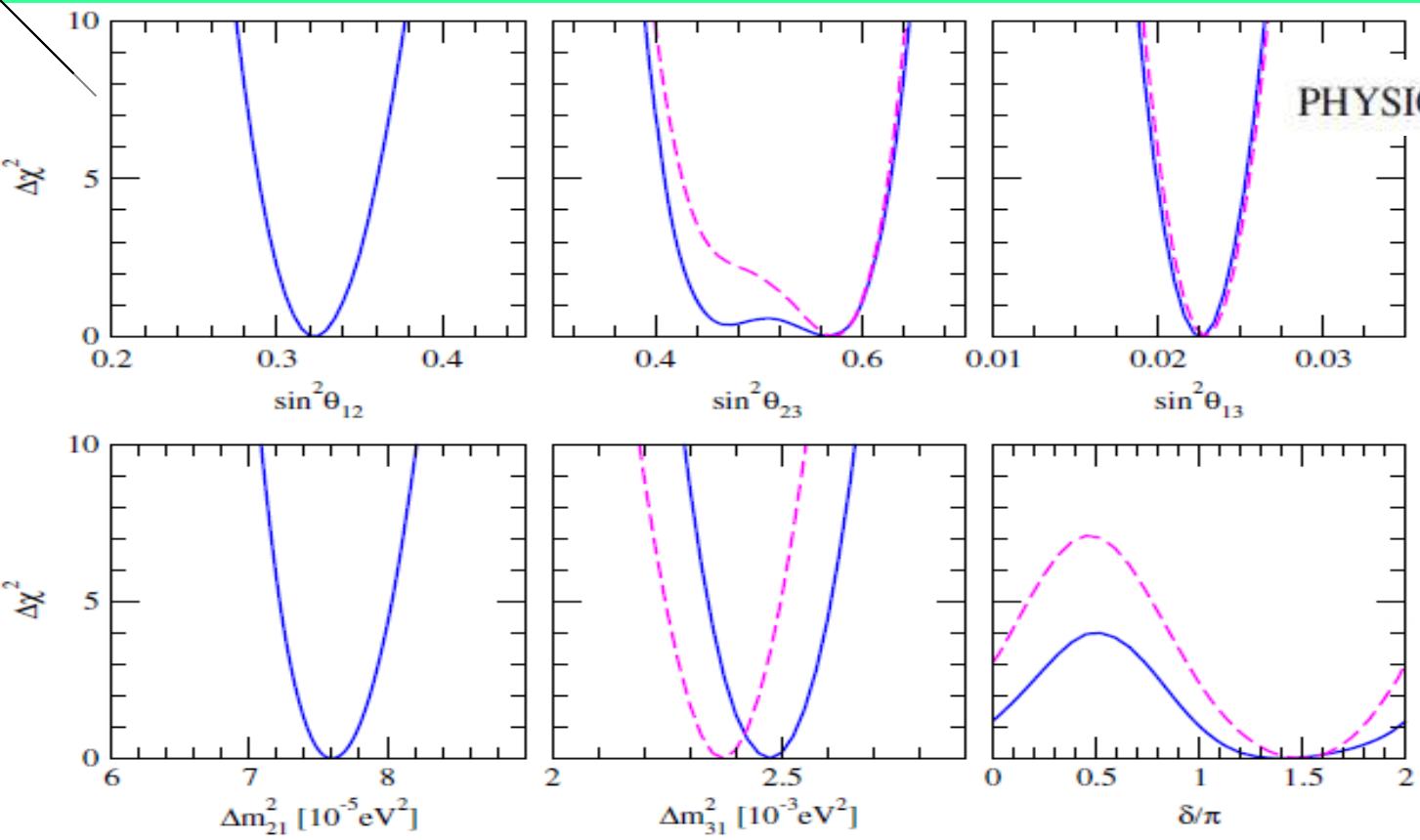
<http://arxiv.org/abs/arXiv:1705.06320>

## Cabbibo as seed?

<http://arxiv.org/abs/arXiv:1706.00210>

## Spectrum predictions





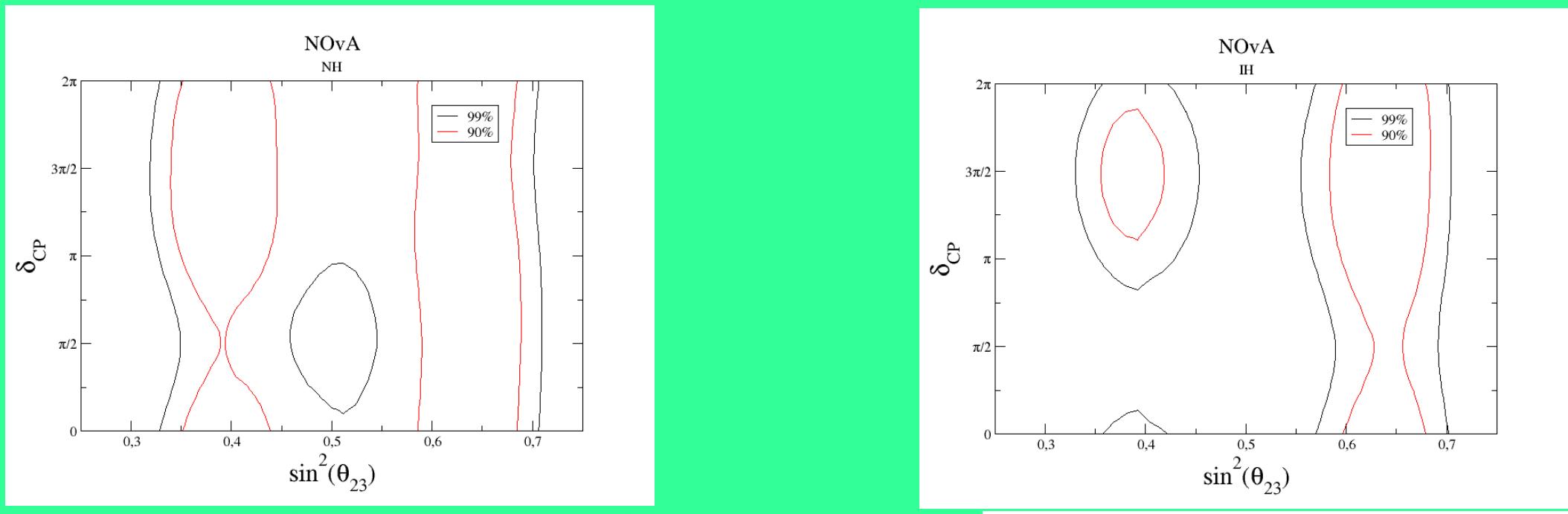
PHYSICAL REVIEW D 90, 093006 (2014)



# the problem with Super-Katm

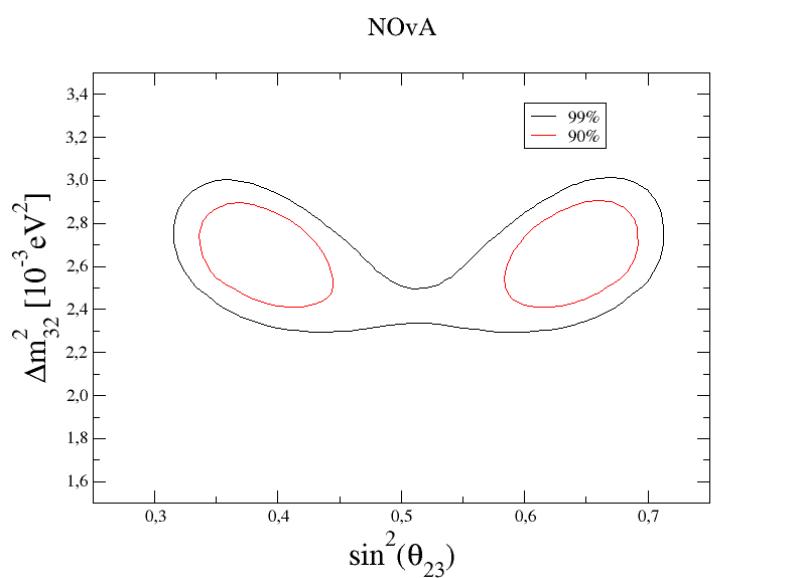
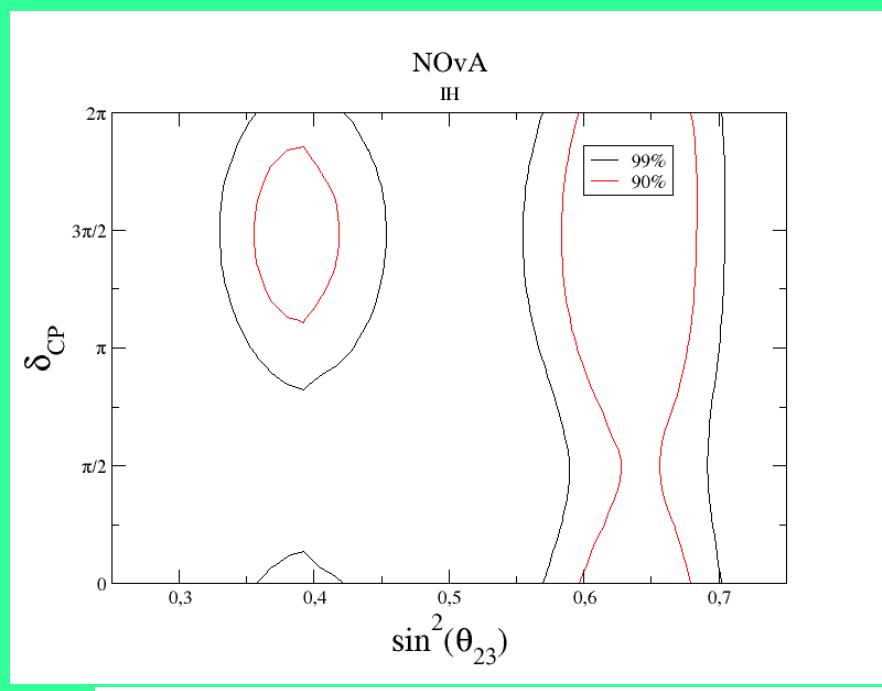
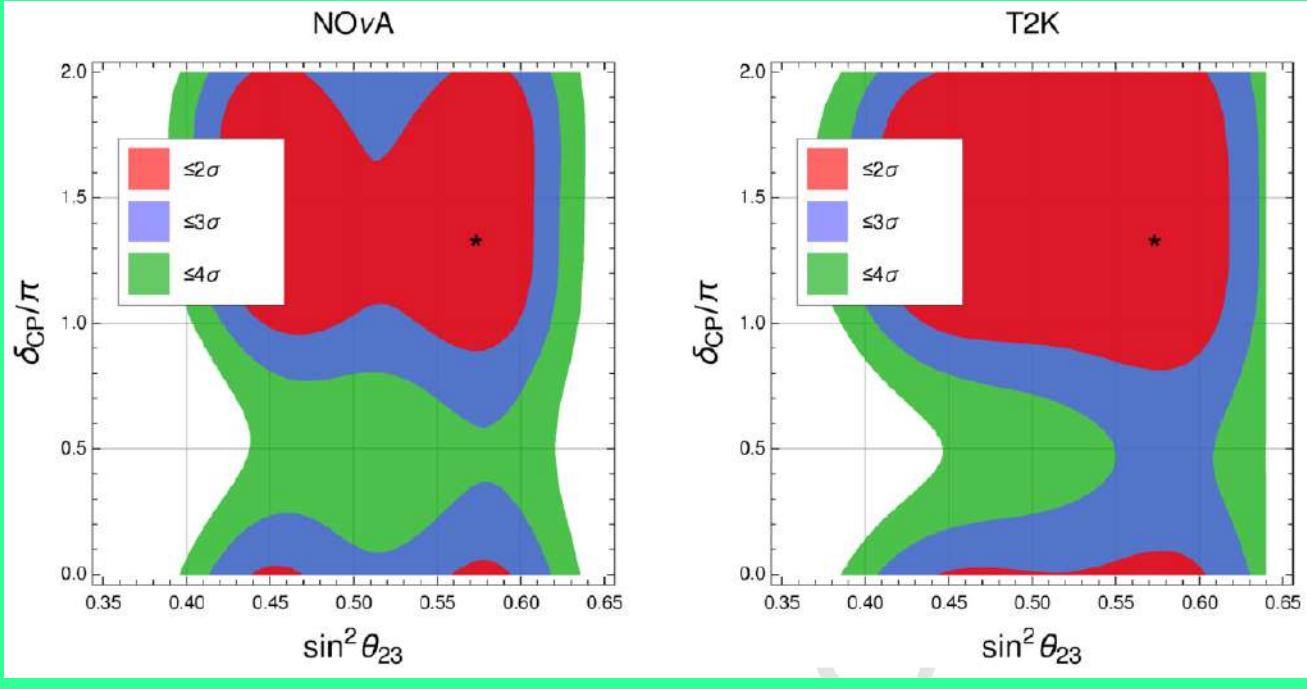
Forero et al include (incomplete) sample, but “safe” .. directly from expt ..  
 Gonzalez-Garcia et al removes atm data, does not include them at all  
 Fogli et al performs a “theory” simulation .. reliability?

# Growing importance of T2K & NovA impact



# T2K & NOvA potential

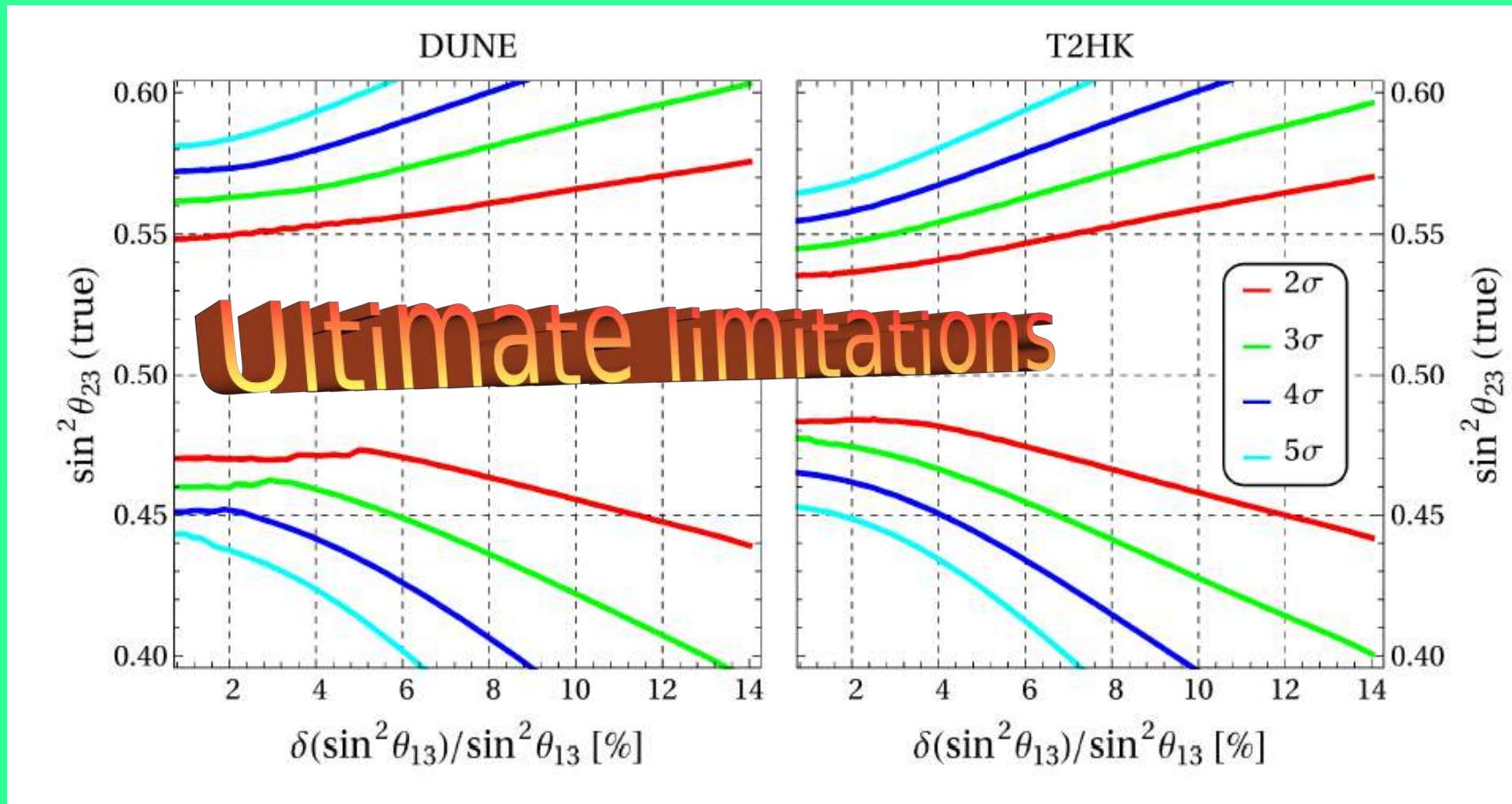
10.1016/j.physletb.2017.05.080



# Icecube KM3net

# Probing octant: the role of t<sub>13</sub>

<https://arxiv.org/pdf/1702.03160.pdf>



Resolving the atmospheric octant by an improved measurement of the reactor angle

FIG. 3. Octant discrimination potential as a function of the relative error on  $\sin^2 \theta_{13}$  for the true value of  $\delta_{CP}^{\text{TRUE}} = 1.34\pi$ . The left (right) panel represents the results for DUNE (T2HK). The red, green, blue and cyan curves delimit the  $\theta_{23}$  “octant-blind” region corresponding to 2, 3, 4 and  $5\sigma$  confidence (1 d.o.f).

# Oscillation robustness

Schechter & JV PRD22 (1980) 2227 & PDG

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

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

Valle PLB199, 432 (1987)

# nonunitary lepton mixing

$$\alpha_{11}^2 \geq 0.989, \quad \alpha_{22}^2 \geq 0.999, \quad |\alpha_{21}|^2 \leq 6.6 \times 10^{-4}$$

O.G. Miranda, J.W.F. Valle / Nuclear Physics B 908 (2016) 436–455

Escrihuela, Forero, Miranda, Tórtola & Valle PhysRevD.92.053009

$$P_{\mu e} = \alpha_{11}^2 \alpha_{22}^2 P_{\mu e}^{3 \times 3} + \underline{\alpha_{11}^2 \alpha_{22} |\alpha_{21}| P_{\mu e}^I} + \alpha_{11}^2 |\alpha_{21}|^2$$

PRL 117, 061804 (2016) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2016

## New Ambiguity in Probing CP Violation in Neutrino Oscillations

O. G. Miranda,<sup>1,\*</sup> M. Tórtola,<sup>2,†</sup> and J. W. F. Valle<sup>2,‡</sup>

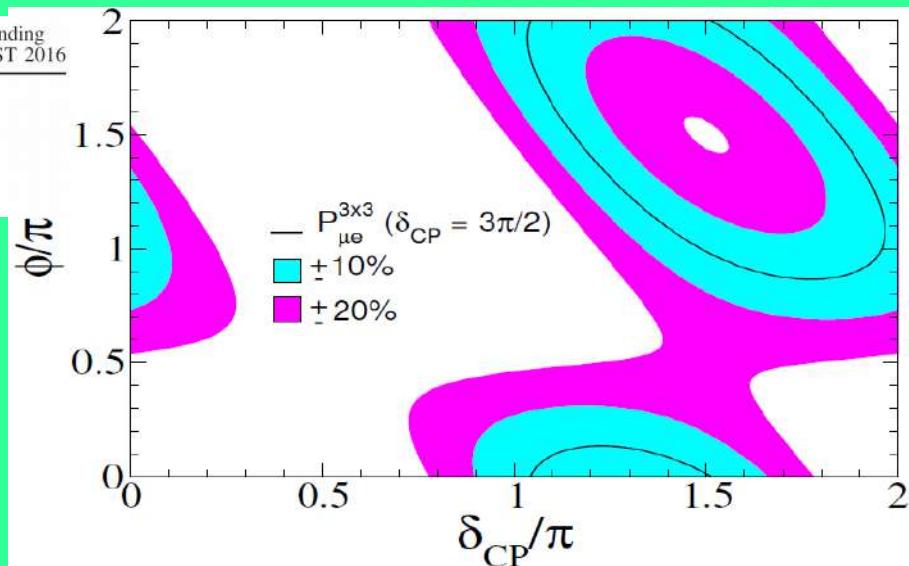
# Implications for future

<http://dx.doi.org/10.1103/PhysRevD.95.033005>

<http://arxiv.org/abs/arXiv:1612.07377>

# Where is the new physics?

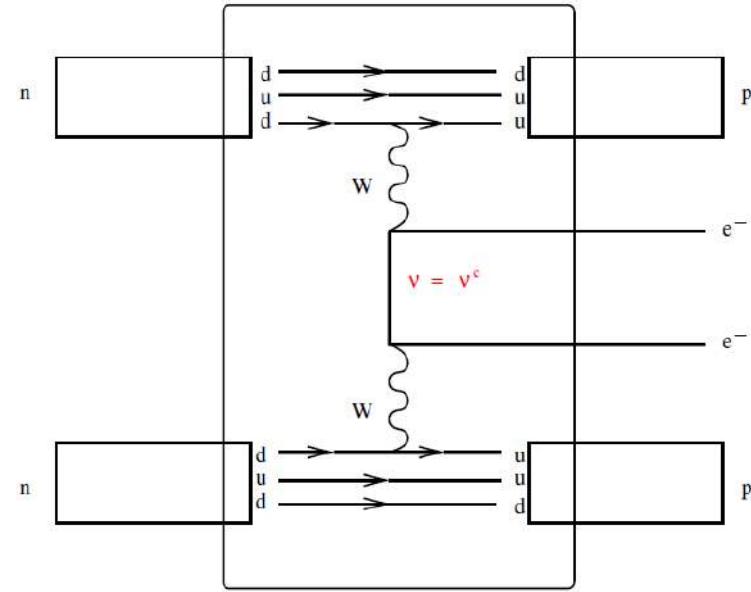
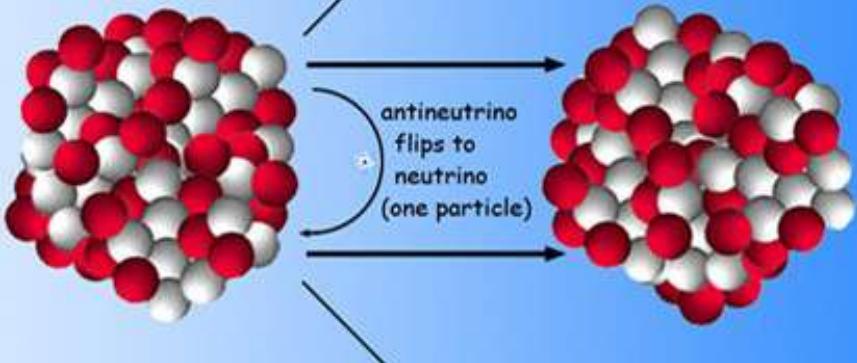
# CP confusion



# probing neutrino mass scale

# Neutrinoless Double Beta Decay

A.S. Barabash arXiv:1104.2714



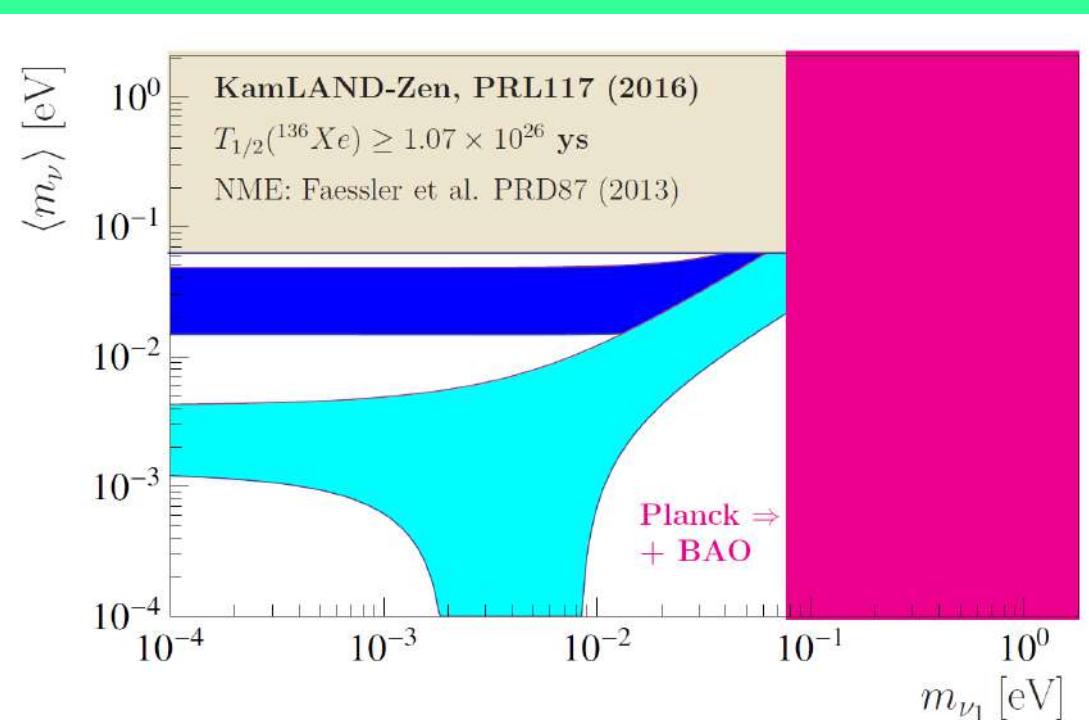
<http://medex17.utef.cvut.cz/>

Link to nEXO (proposed successor to EXO-200):

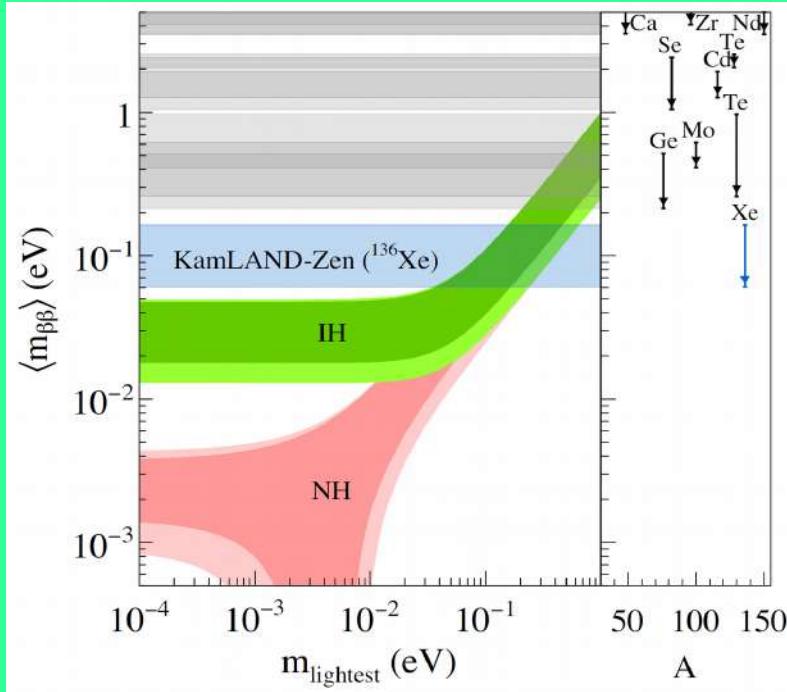
<http://medex17.utef.cvut.cz/talks/Gratta.pdf>

Link to LEGEND (successor to GERDA/Majorana):

<http://medex17.utef.cvut.cz/talks/Wilkerson.pdf>

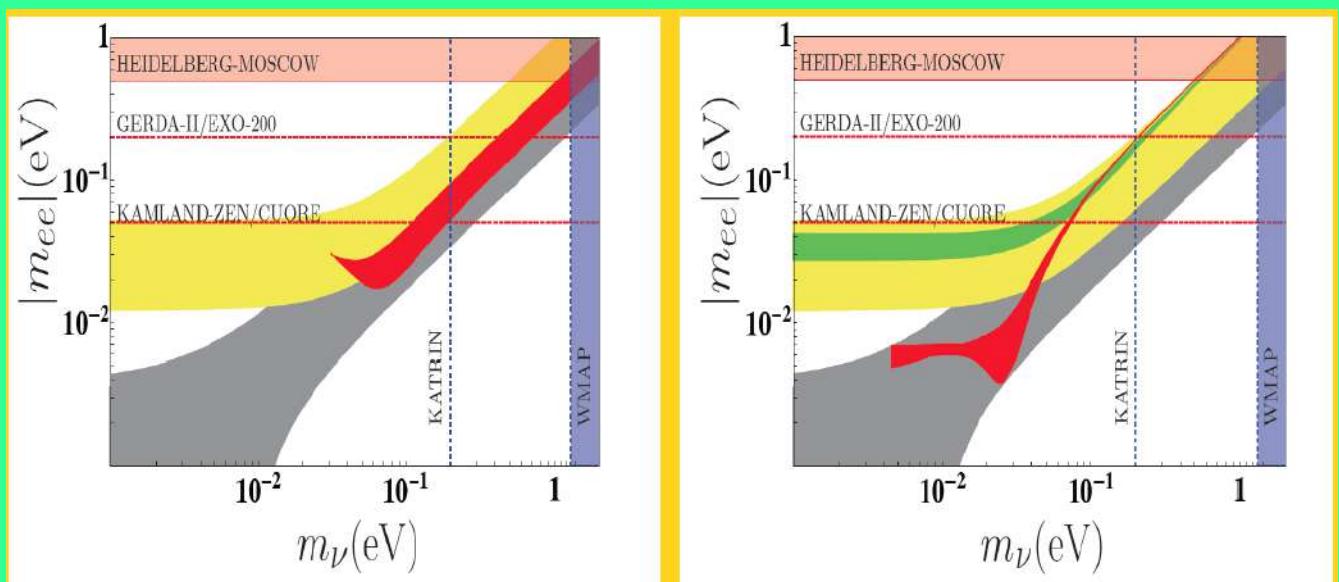


# Flavor Sensitivity neutrinoless $\beta\beta$ decay



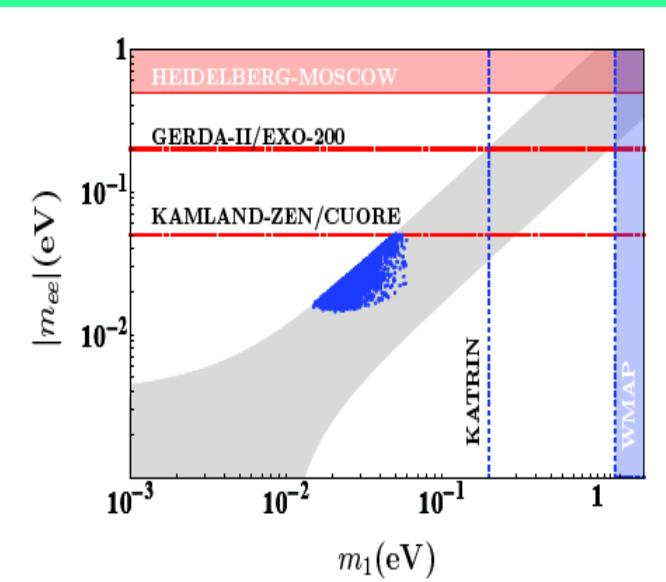
A.S. Barabash arXiv:1104.2714

Lower bounds even for NH ...



Dorame et al  
NPB861 (2012) 259-270

Dorame et al,  
PhysRevD.86.056001



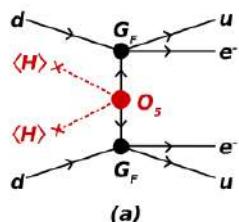
King et al Phys. Lett. B 724 (2013)  
15



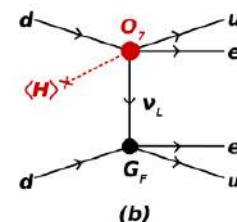
# the Majorana connection

Päs et al, PLB453 (1999)

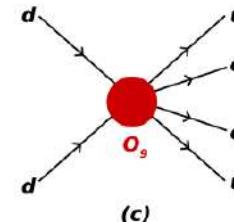
Amplitude for  $(Z, A) \rightarrow (Z \pm 2, A) + e^\mp e^\mp$  can be divided into: & PLB498 (2001)



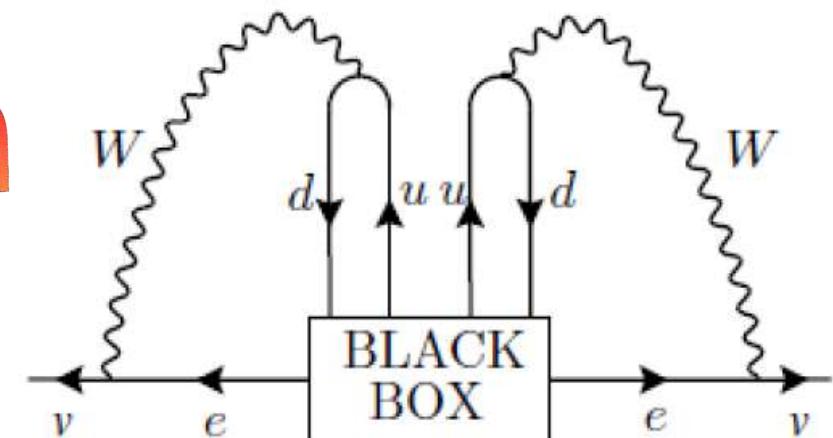
Mass mechanism



"long-range"

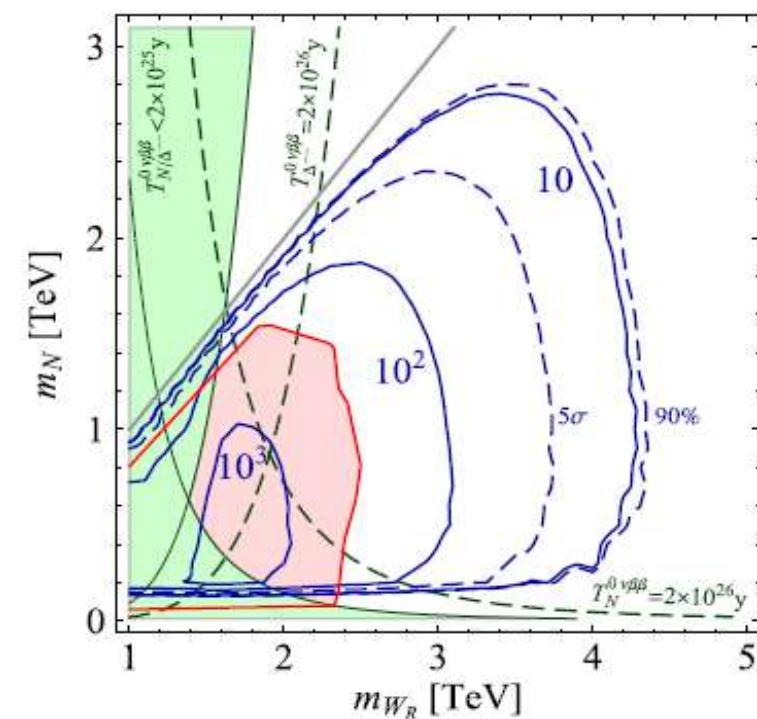
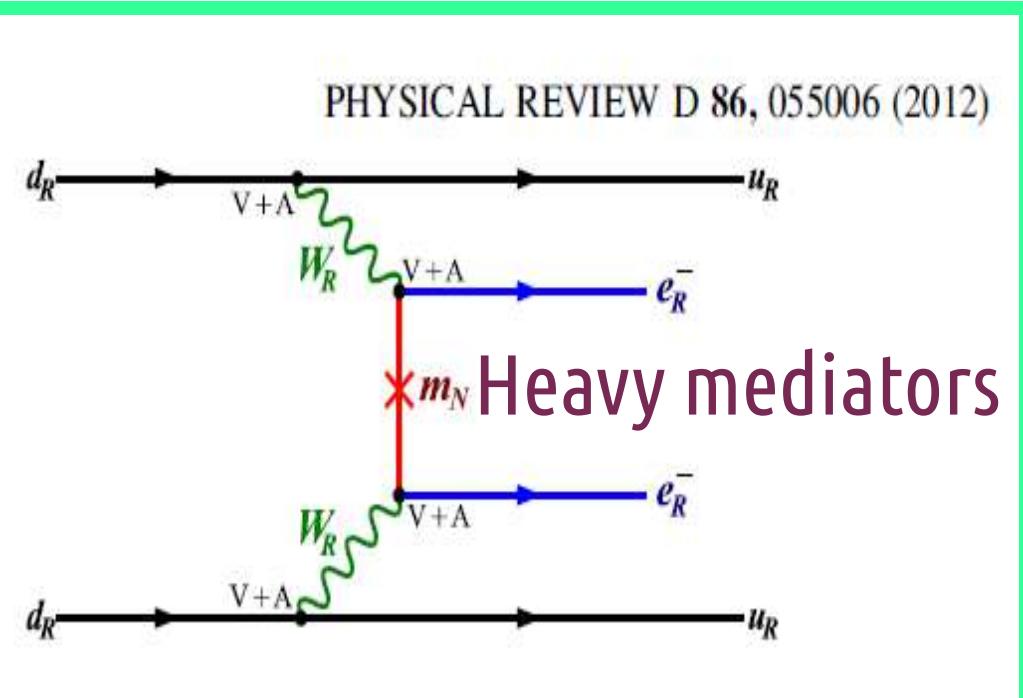


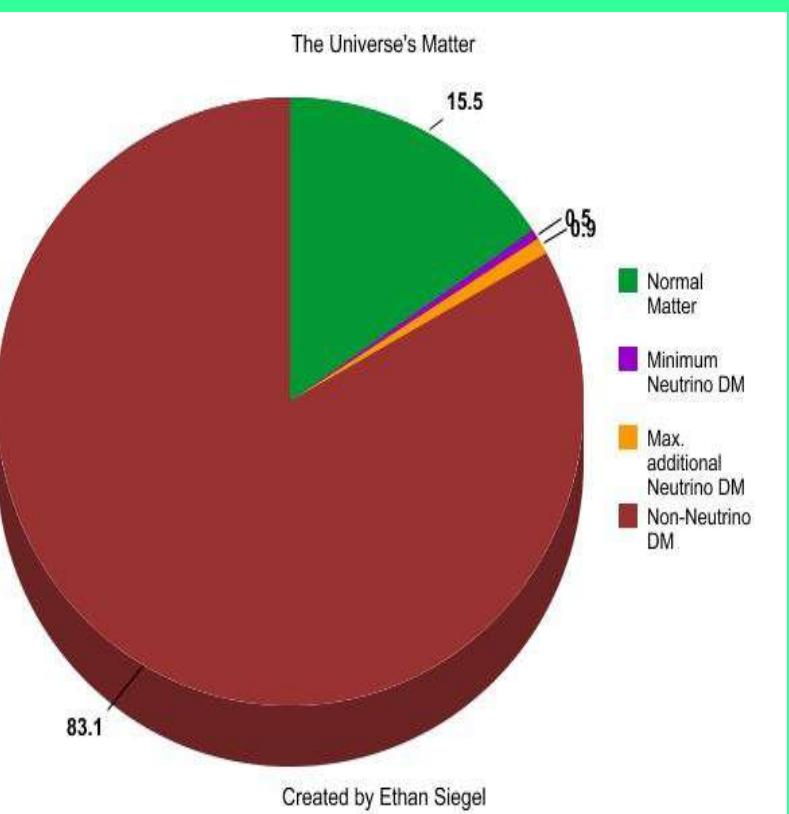
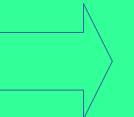
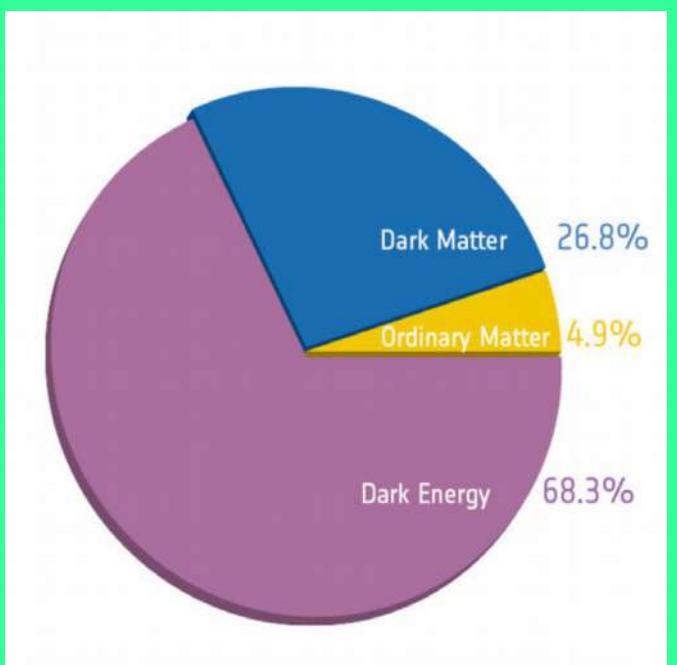
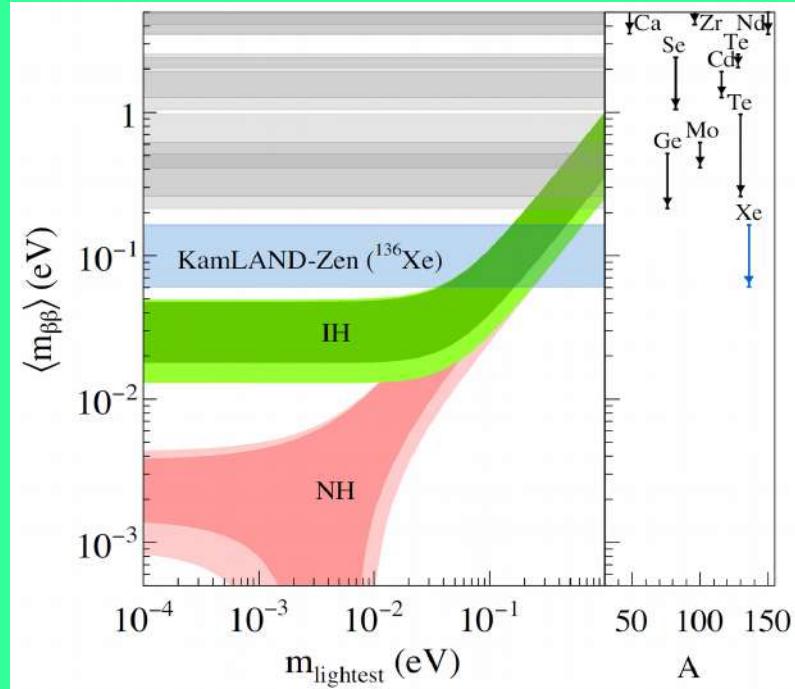
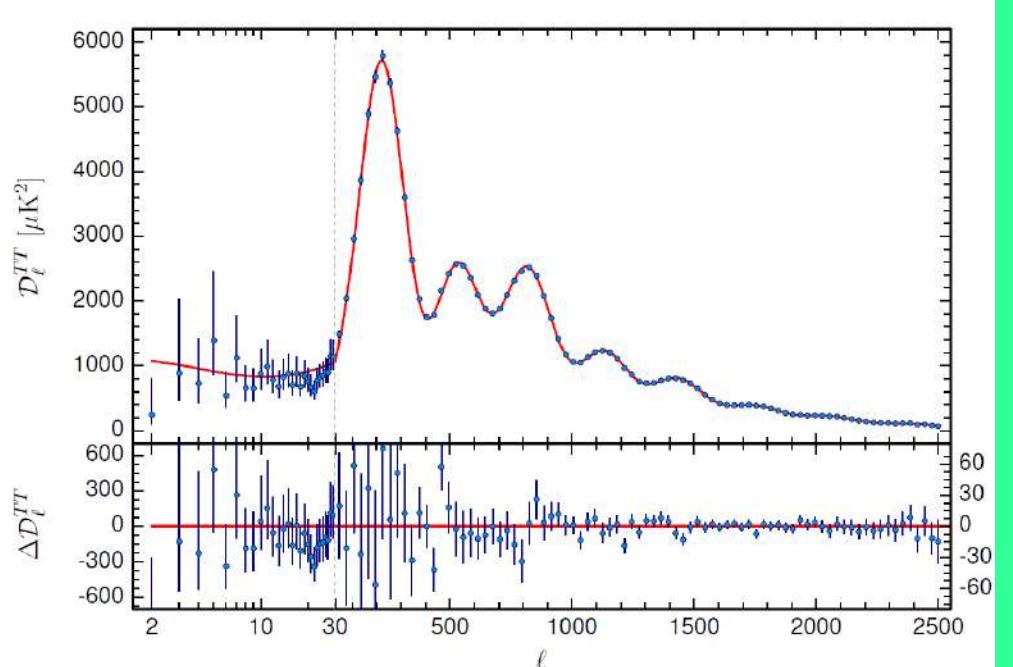
"short-range"



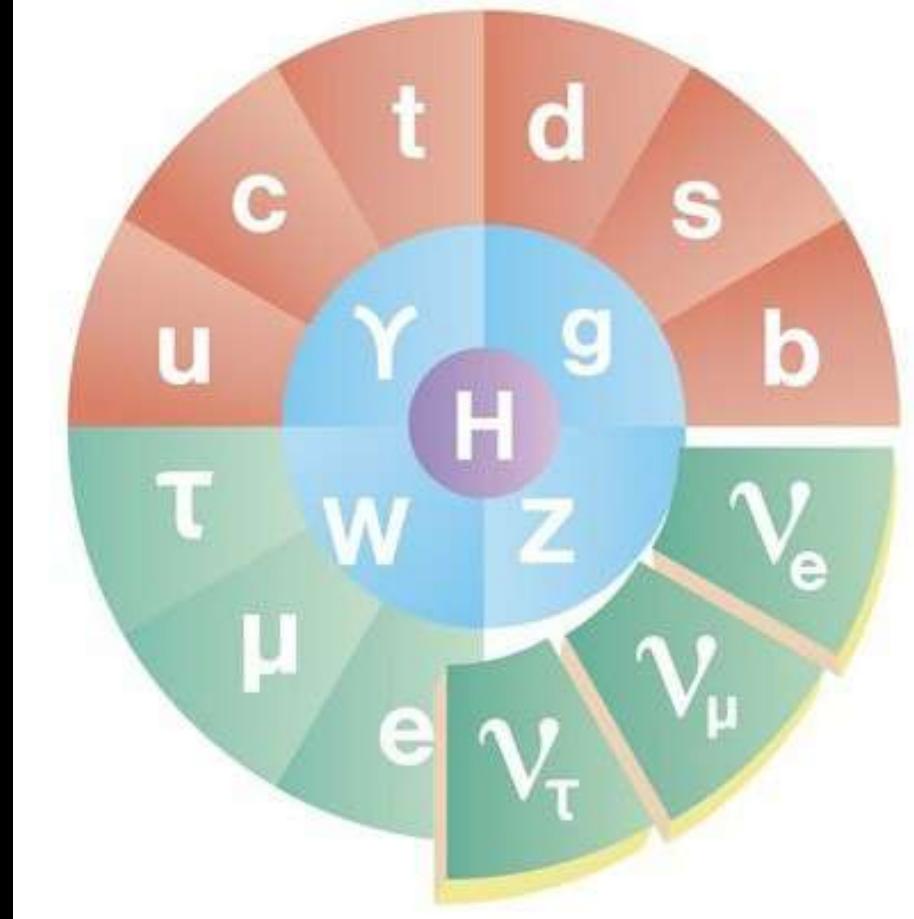
Schechter, Valle 82  
Lindner et al JHEP 1106 (2011) 091

PHYSICAL REVIEW D 86, 055006 (2012)





# However exciting ...



## Higgs not the last brick !

# Standard model

does not  
explain

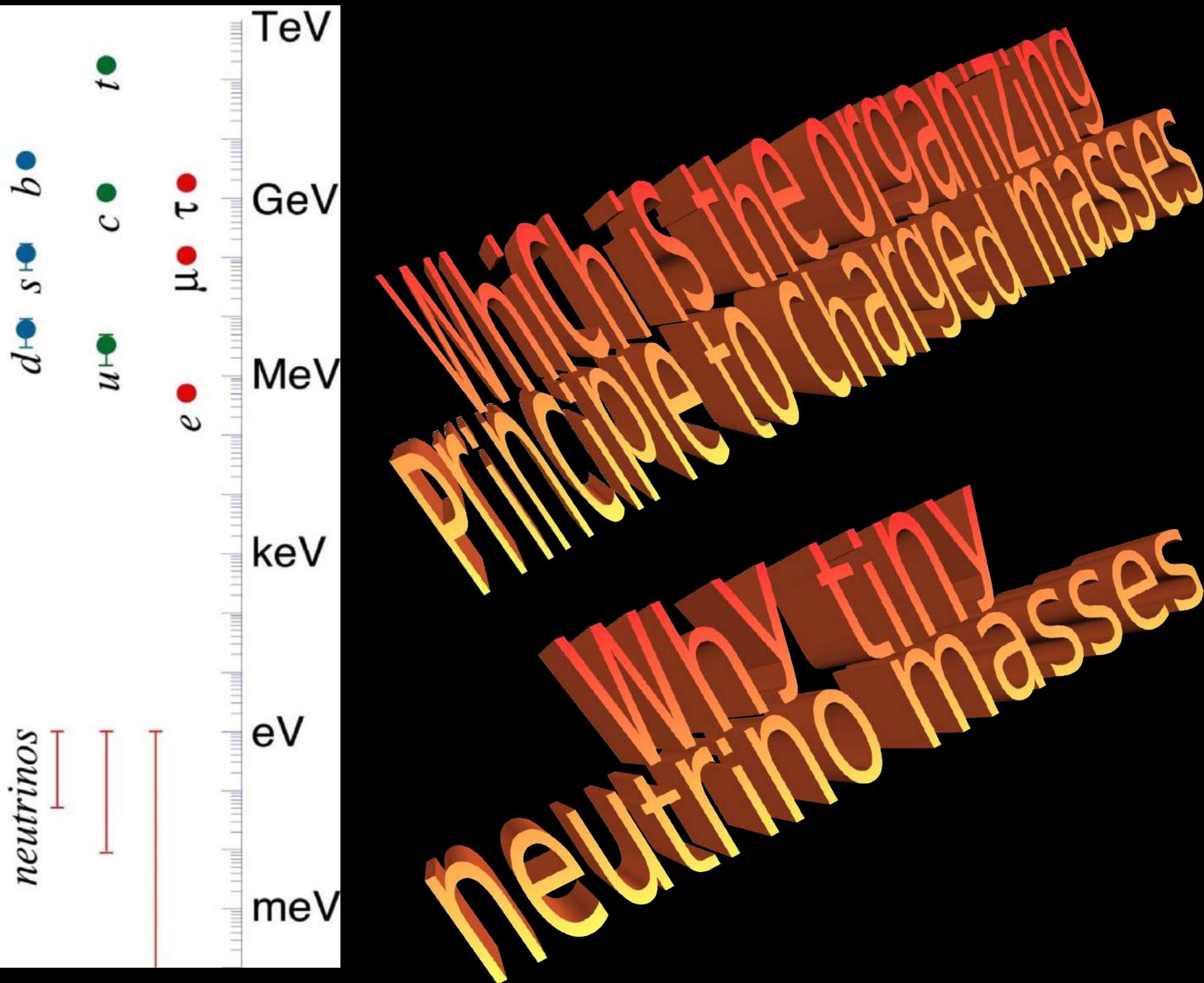
- Anomalies,
- unification,
- consistency of EWSB,
- Gravity
- Flavor

*Neutrino mass +  
Cosmology, e.g.  
dark matter, inflation,  
Baryogenesis, dark energy*

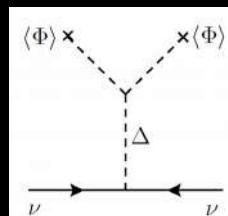
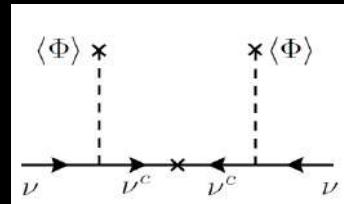
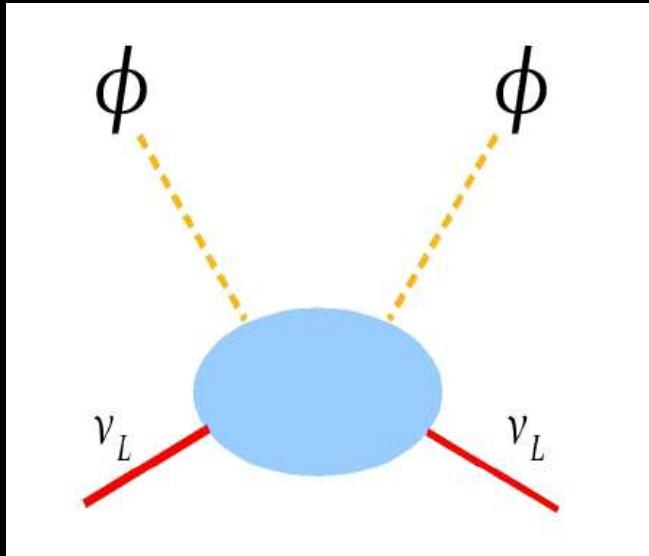
# lecture 2

- Dirac & Majorana neutrino mass
- Theoretical origin
- Flavor problem
- Explaining masses, mixings & correlations
- Neutrino mass in EW breaking
- Dark matter and neutrinos
- Majoron Dark matter
- Dark matter and flavor problem
- Dark matter and Diracness
- Neutrinoless  $\beta\beta$  & quadruple  $\beta$  decay
- Neutrinos & other cosmological puzzles
- Towards the TOE: Comprehensive unification

# theory



# 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

Schechter-Valle 80/82

$$v_3 v_1 \sim v_2^2$$

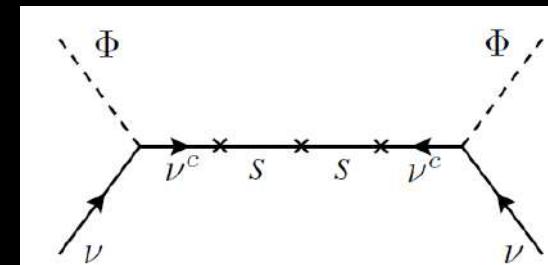
# Seesaw

coefficient  
 Mechanism  
 Scale  
 Flavor structure

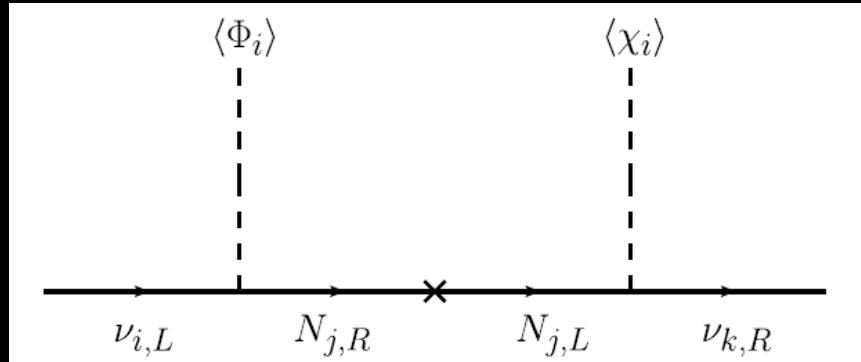
Number & properties of messengers

## LOW-SCALE SEESAW

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



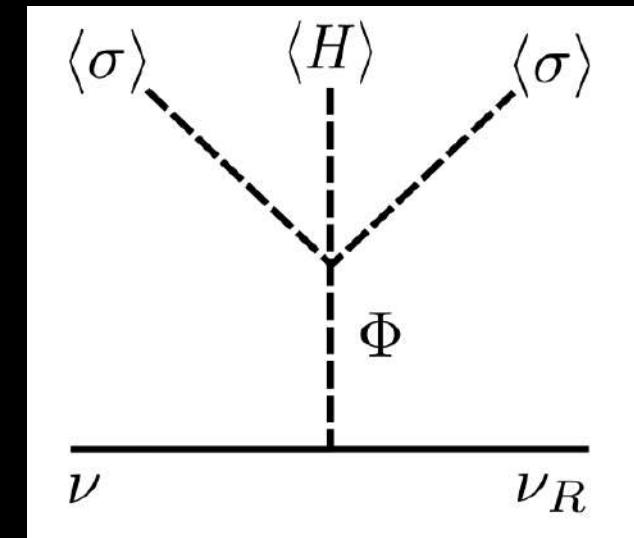
# seesaw mechanism for Dirac neutrinos



**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

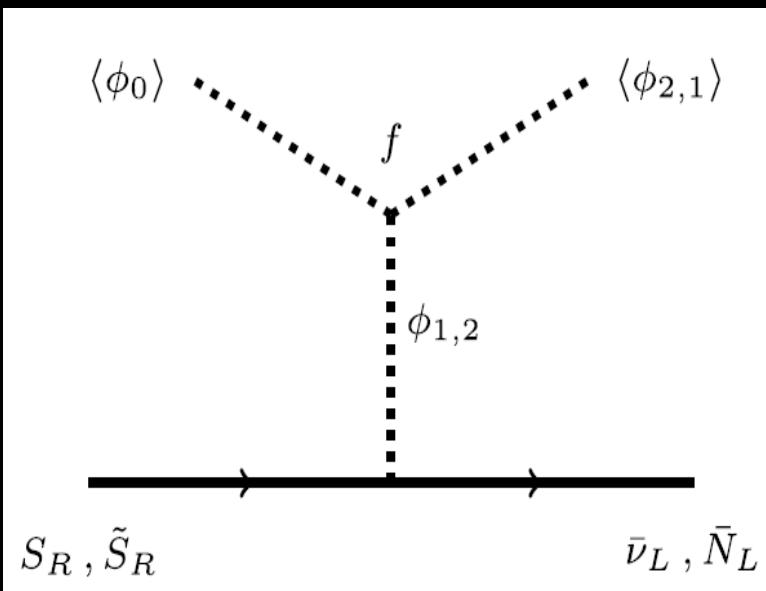
## Spontaneous versus explicit U(1) symmetry violation

## String context



# Dirac seesaw

Addazi et al arXiv:1604.02117



Physics Letters B 755 (2016) 363–366

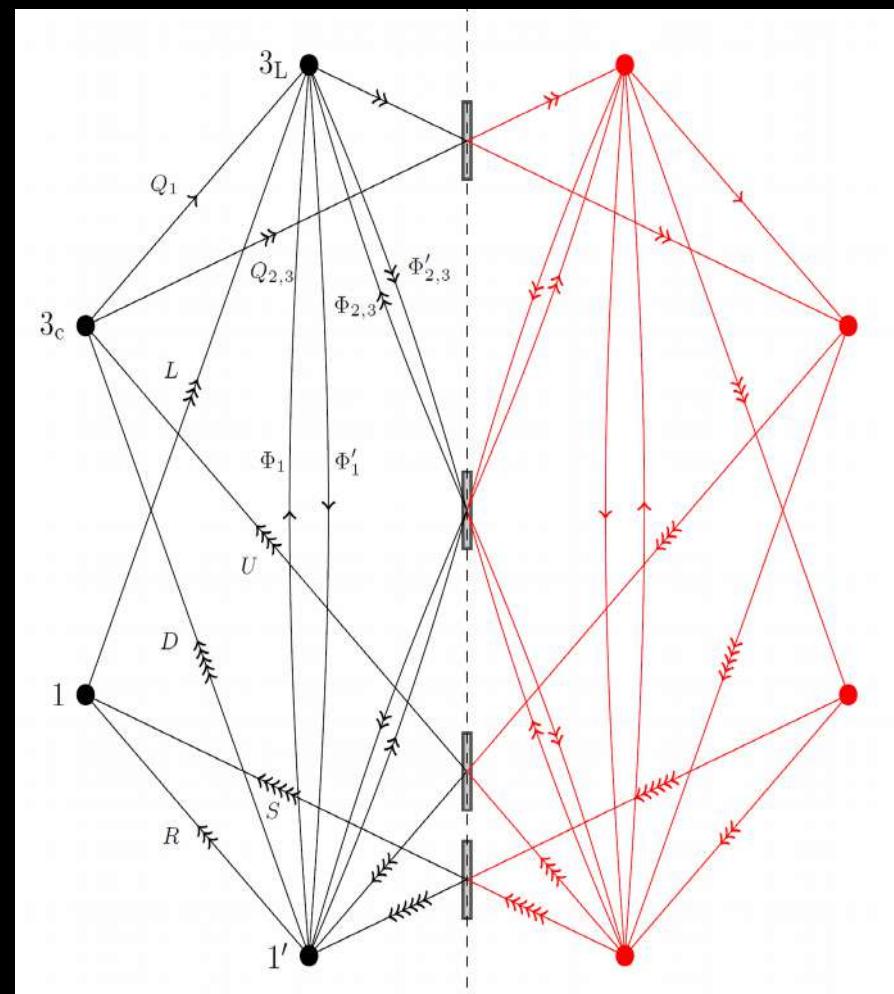
No conventional GUT embedding :

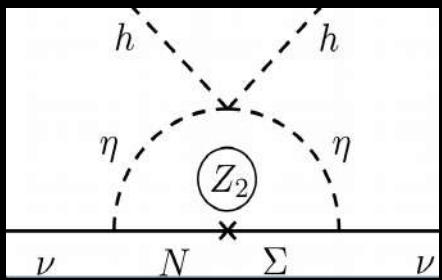
<http://arxiv.org/abs/arXiv:1608.05334>

string completion Quiver setup

# From Strings

10.1016/j.physletb.2016.06.015





# Radiative neutrino mass

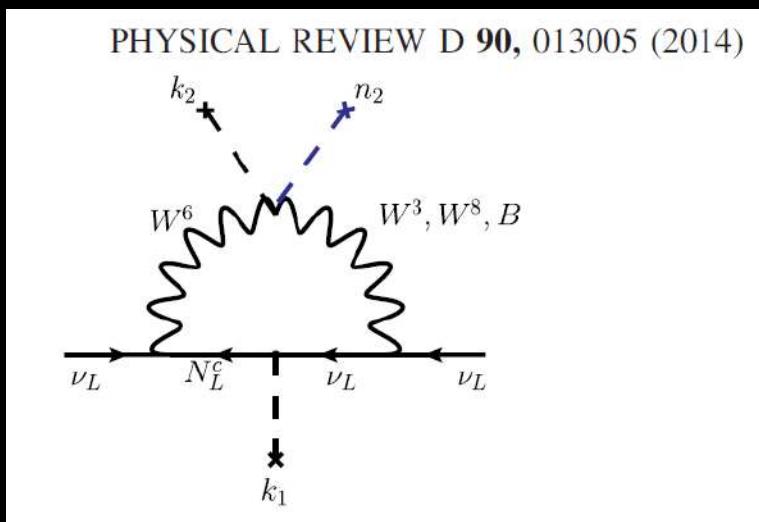
many low-scale neutrino mass schemes ...

arXiv:1404.3751

E Ma, Merle et al JHEP 1607 (2016) 013  
Hirsch et al JHEP 1310 (2013) 149

**331 EW theory** # families = # colours  
Singer, Valle, Schechter, Phys.Rev. D22 (1980) 738

## Gauge vs Higgs



BOUCENNA, MORISI, AND VALLE

TABLE I. Matter content of the model, where  $\hat{u}_R \equiv (u_R, c_R, t_R, t'_R)$  and  $\hat{d}_R \equiv (d_R, s_R, b_R, d'_R, s'_R)$  (see text).

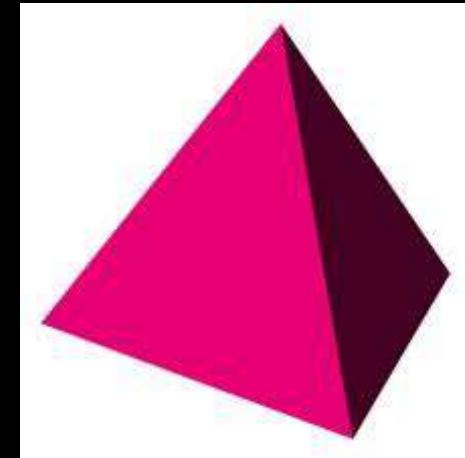
	$\psi_L^\ell$	$\ell_R$	$Q_L^{1,2}$	$Q_L^3$	$\hat{u}_R$	$\hat{d}_R$	$S$	$\phi_1$	$\phi_2$	$\phi_3$
$SU(3)_c$	<b>1</b>	<b>1</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>
$SU(3)_L$	<b>3*</b>	<b>1</b>	<b>3</b>	<b>3*</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>3*</b>	<b>3*</b>	<b>3*</b>
$U(1)_X$	$-\frac{1}{3}$	-1	0	$+\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	0	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
$\mathcal{L}$	$-\frac{1}{3}$	-1	$-\frac{2}{3}$	$+\frac{2}{3}$	0	0	1	$+\frac{2}{3}$	$-\frac{4}{3}$	$+\frac{2}{3}$

$$Q = T_3 + \frac{1}{\sqrt{3}} T_8 + X, \quad (2)$$

$$L = \frac{4}{\sqrt{3}} T_8 + \mathcal{L}. \quad (3)$$

$(\nu_e)$	$(\nu_\mu)$	$(\nu_\tau)$
$e_L$	$\mu_L$	$\tau_L$
$e_R$	$\mu_R$	$\tau_R$
$(u)$	$(c)$	$(t)$
$d_L$	$s_L$	$b_L$
$u_R$	$c_R$	$t_R$
$d_R$	$s_R$	$b_R$

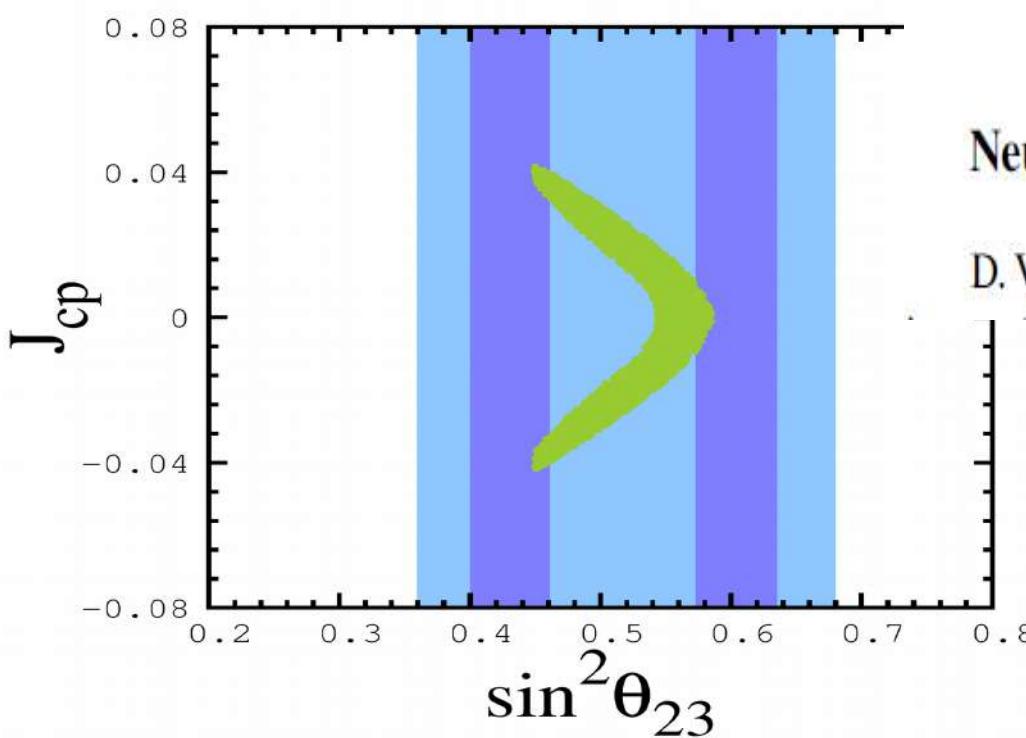
# Flavor Symmetry



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

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

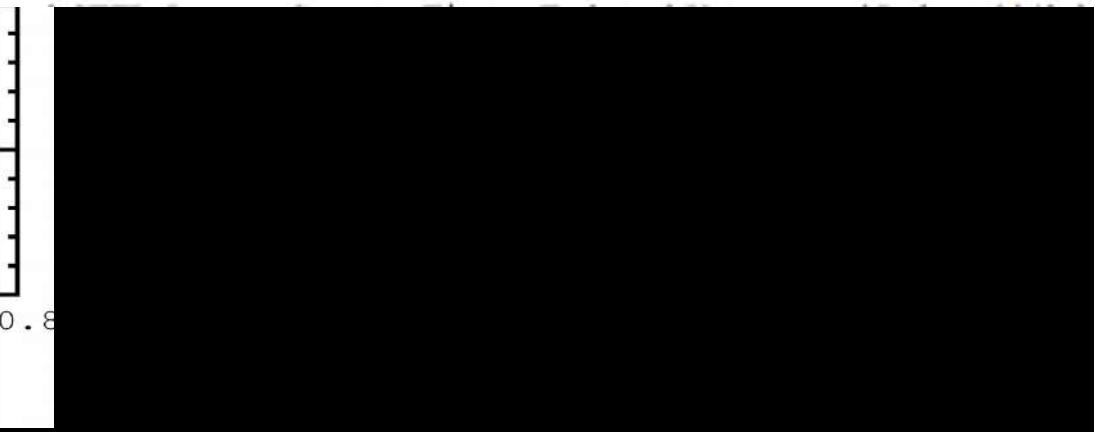
$$\sin^2 \theta_{13} = 0$$



PHYSICAL REVIEW D 88, 016003 (2013)

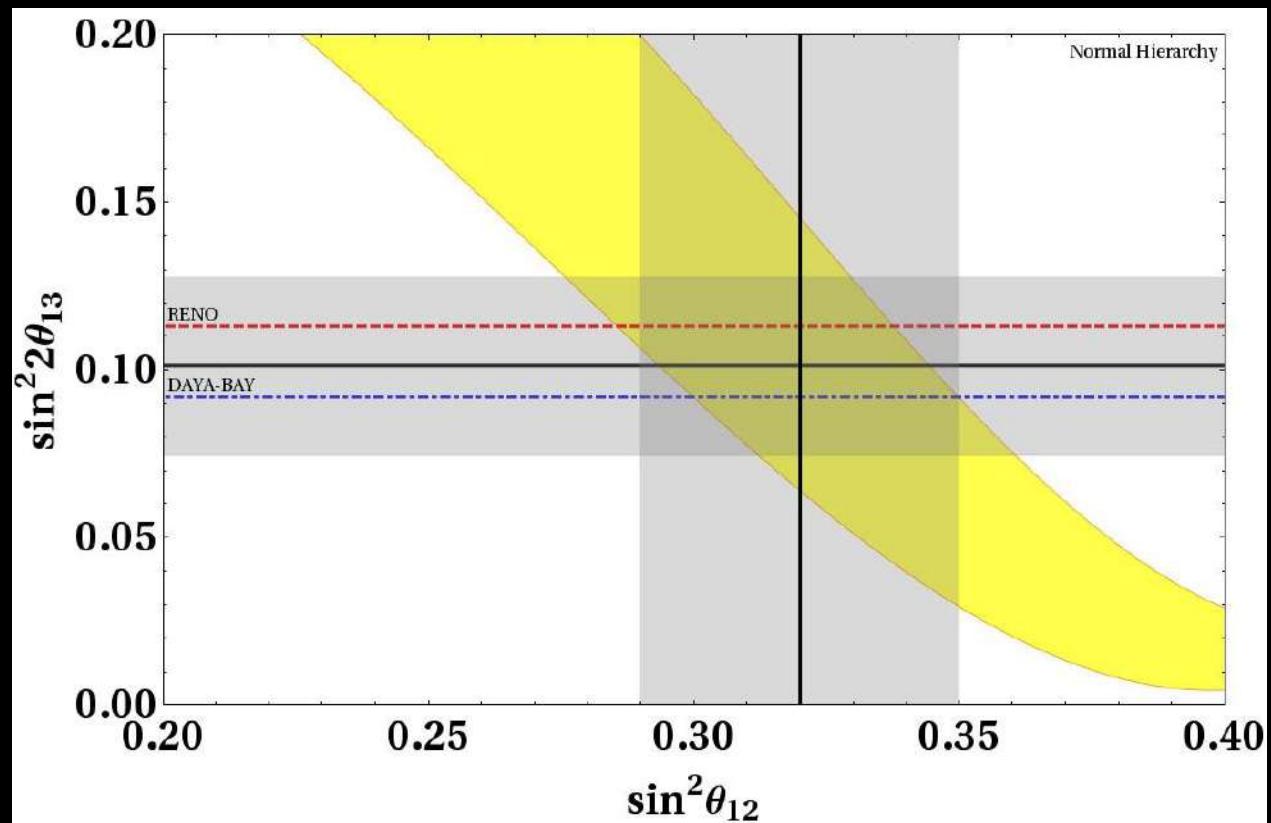
## Neutrino mixing with revamped $A_4$ flavor symmetry

D. V. Forero,<sup>1,2,\*</sup> S. Morisi,<sup>3,†</sup> J. C. Romão,<sup>1,‡</sup> and J. W. F. Valle<sup>2,§</sup>



# Flavor correlations

Boucenna et al  
PhysRevD.86.073008



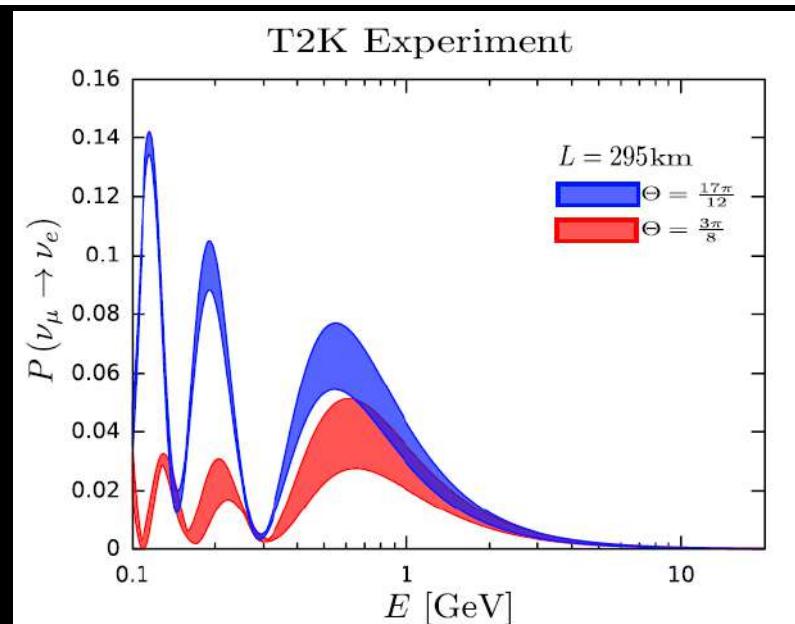
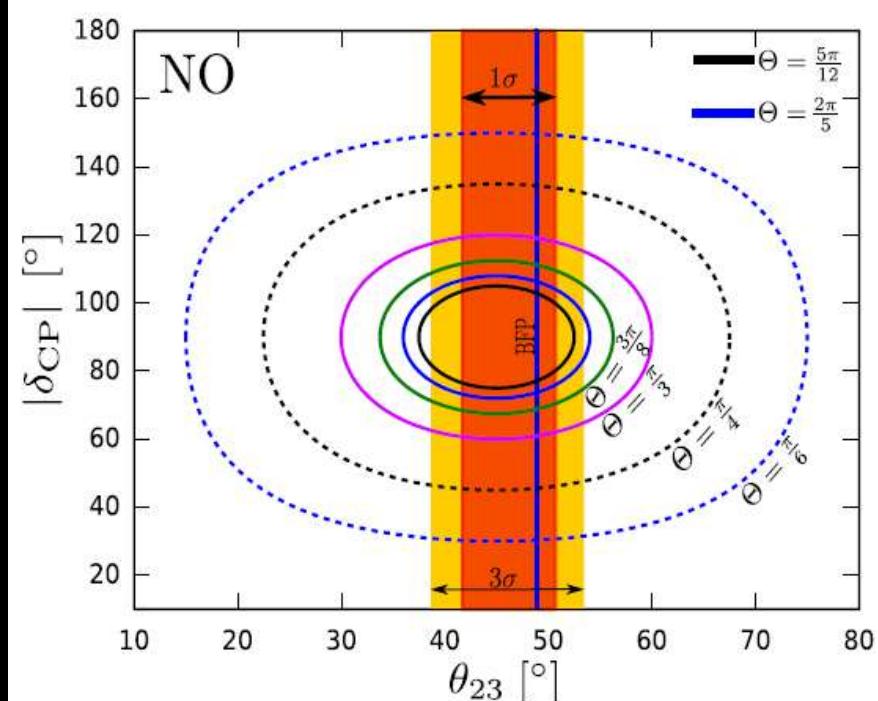
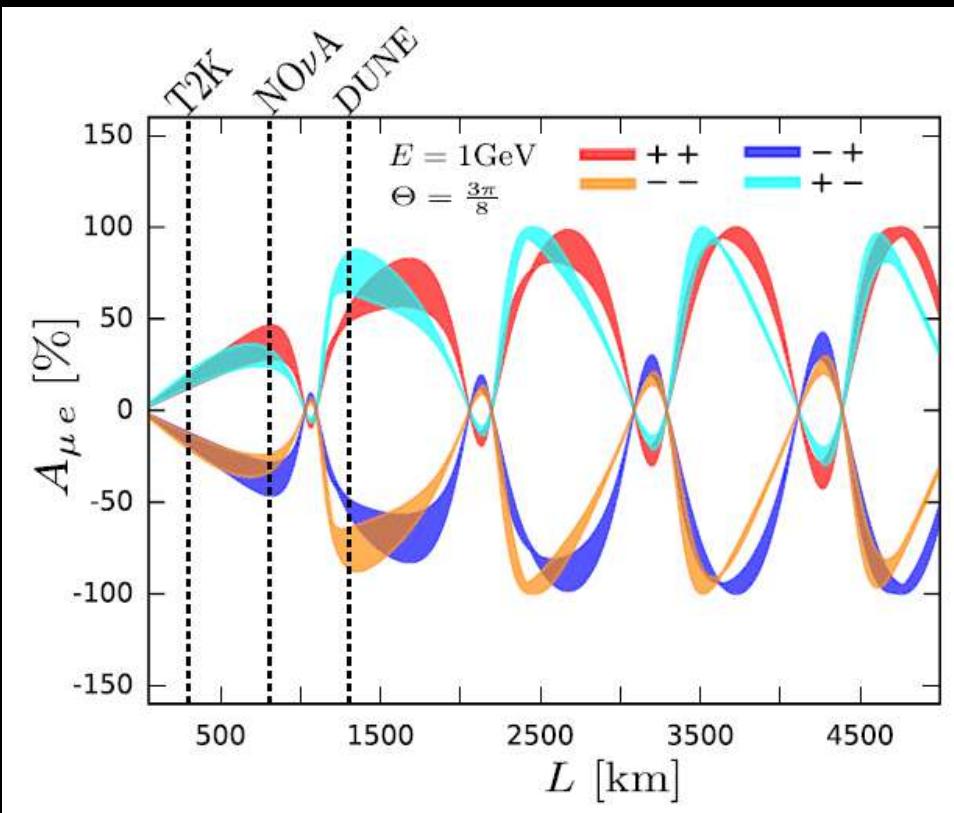
P Chen et al  
Phys.Lett. B753 (2016) 644-652  
Phys.Rev. D94 (2016) no.3, 033002

# Residual CP

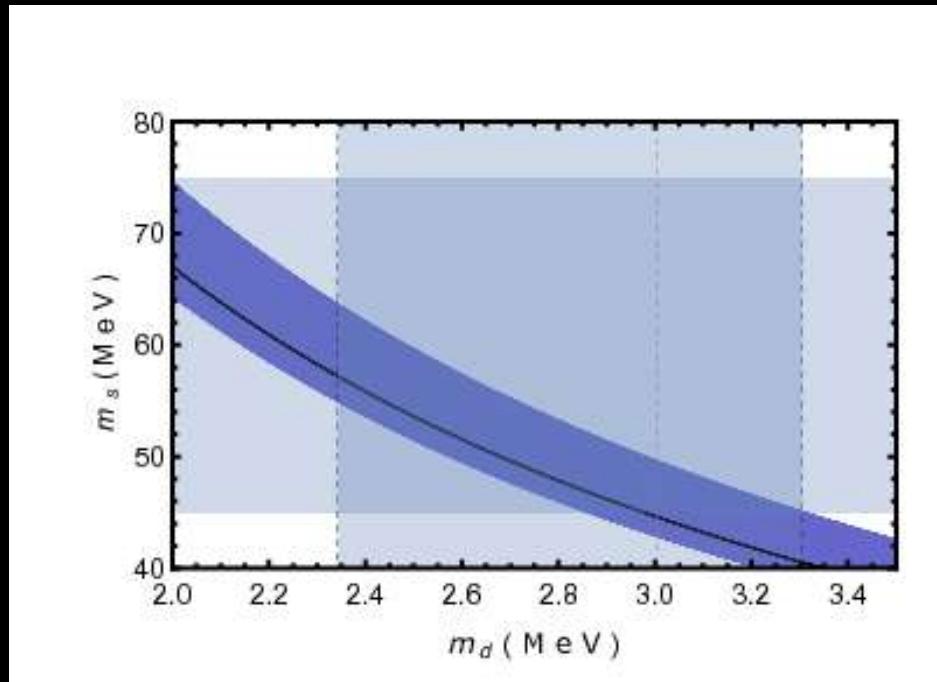
# Model-independent flavor approach

$$\mathbf{X}^T \mathbf{m}_\nu \mathbf{X} = \mathbf{m}_\nu^*$$

Predicting neutrino mixing  
from residual CP symmetries



# charged fermion masses



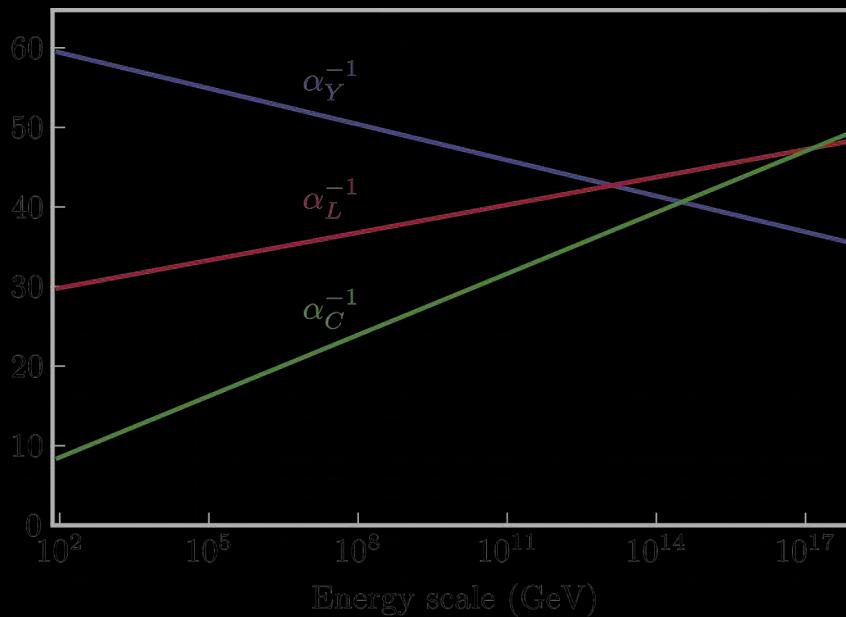
**Flavor dependent  
b-tau unification**

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

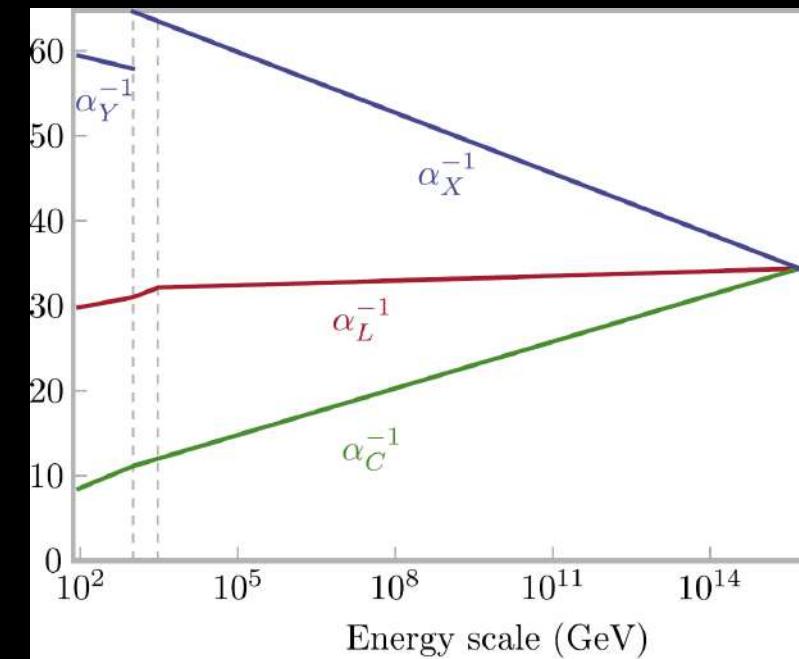
- Morisi et al Phys.Rev. D84 (2011) 036003  
King et al Phys. Lett. B 724 (2013) 68  
Morisi et al Phys.Rev. D88 (2013) 036001  
Bonilla et al Phys.Lett. B742 (2015) 99

**from same symmetry  
explaining oscillations**

# Standard model *a near miss ...*



What makes the gauge couplings unify? SUSY-GUT  
But ... p decay, super-particles ...

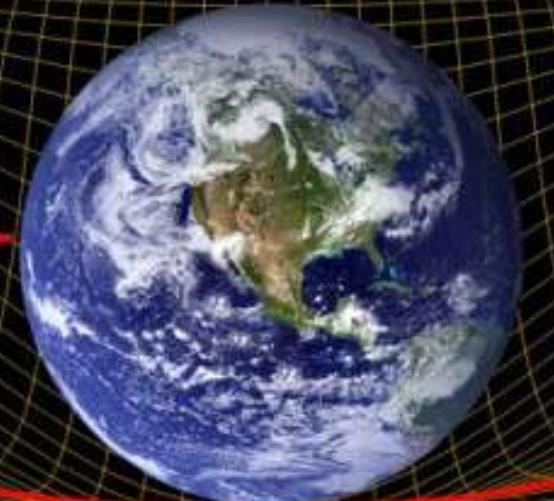


## neutrinos & unification

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

Boucenna et al Phys. Rev. D 91, 031702 (2015)  
Deppisch et al Phys.Lett. B762 (2016) 432

# including Gravity

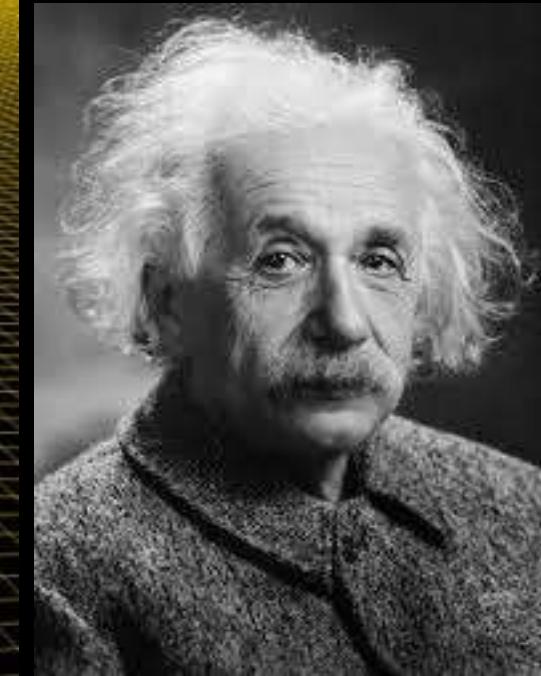


neutrinos in the  
theory of everything

Chen et al arXiv:1509.06683  
JHEP01(2016)007

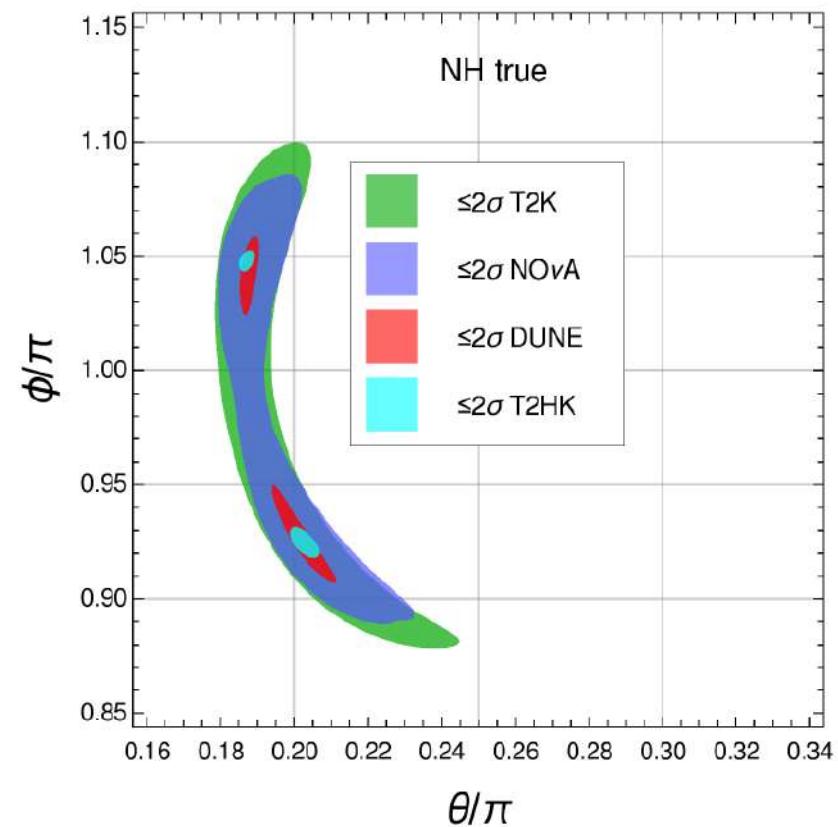
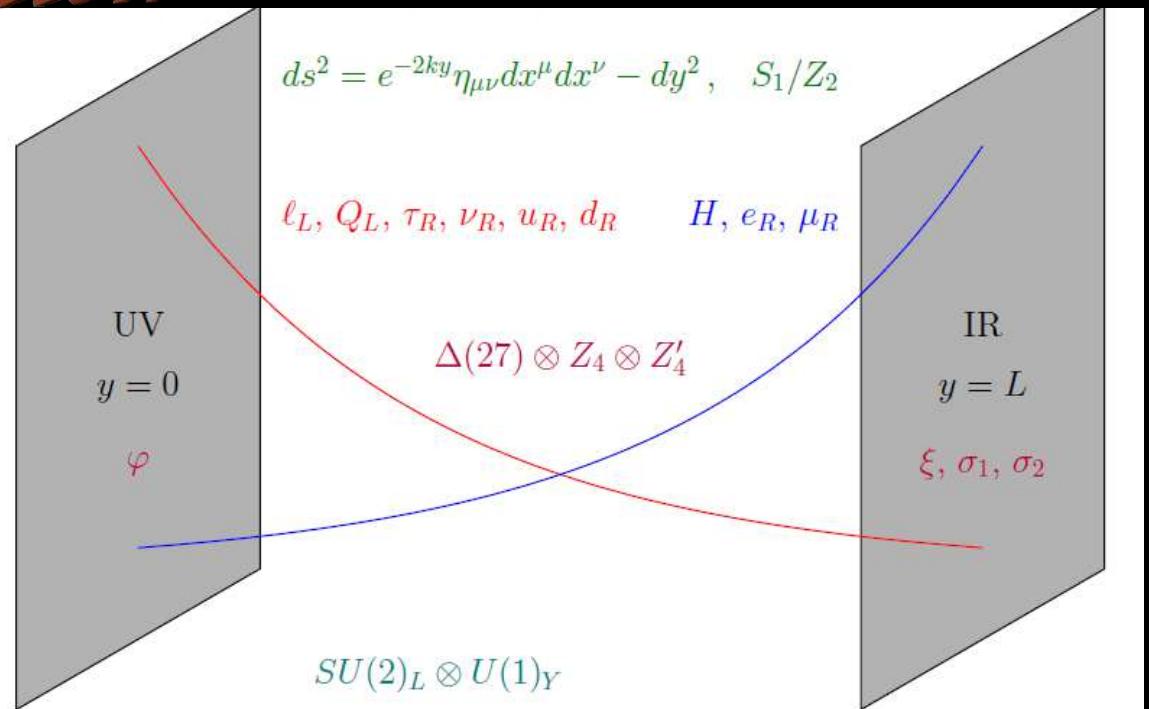
Addazi et al

Phys.Lett. B759 (2016) 471-478



# Warped Standard Model

: Chen et al arXiv:1509.06683  
JHEP01(2016)007



masses explained by bulk parameter choices

mixings

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

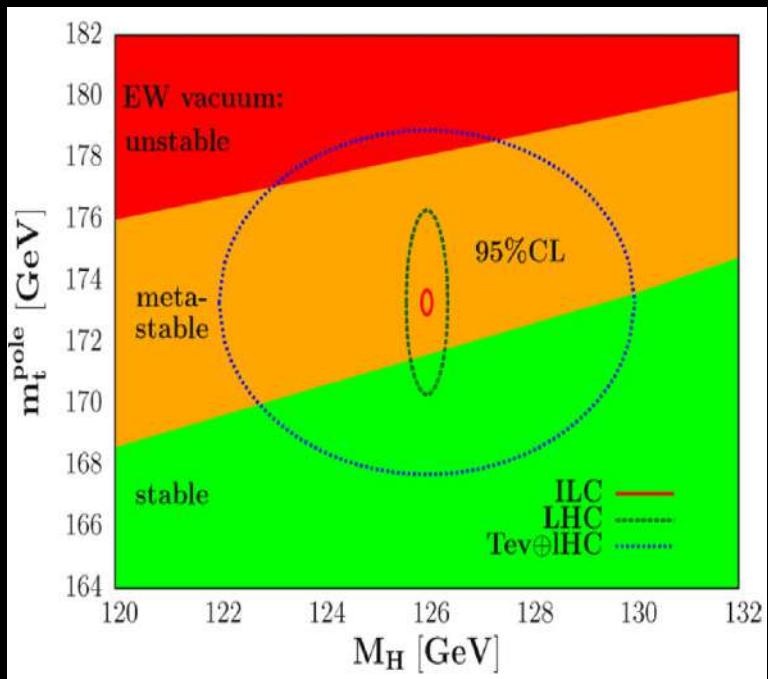
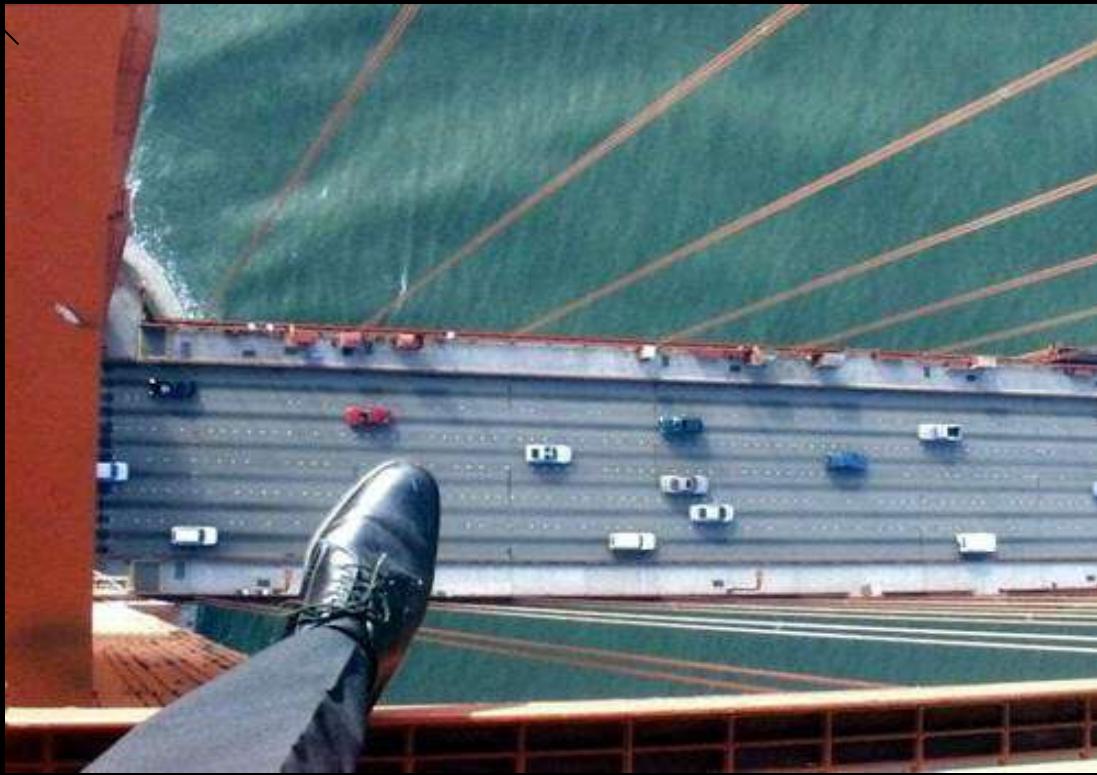
$$\sin^2 \theta_{13} = \frac{1}{3} (1 + \sin 2\theta_v \cos \phi_v)$$

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

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

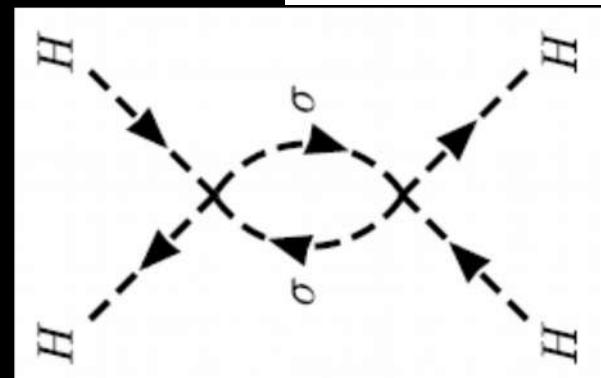
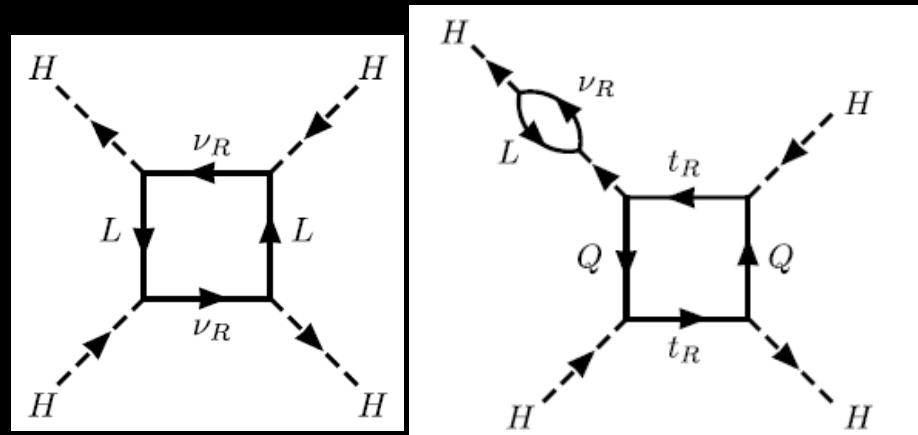
<http://arxiv.org/abs/arXiv:1610.05962>

predictions for  
neutrino oscillations



# SM vacuum and neutrinos

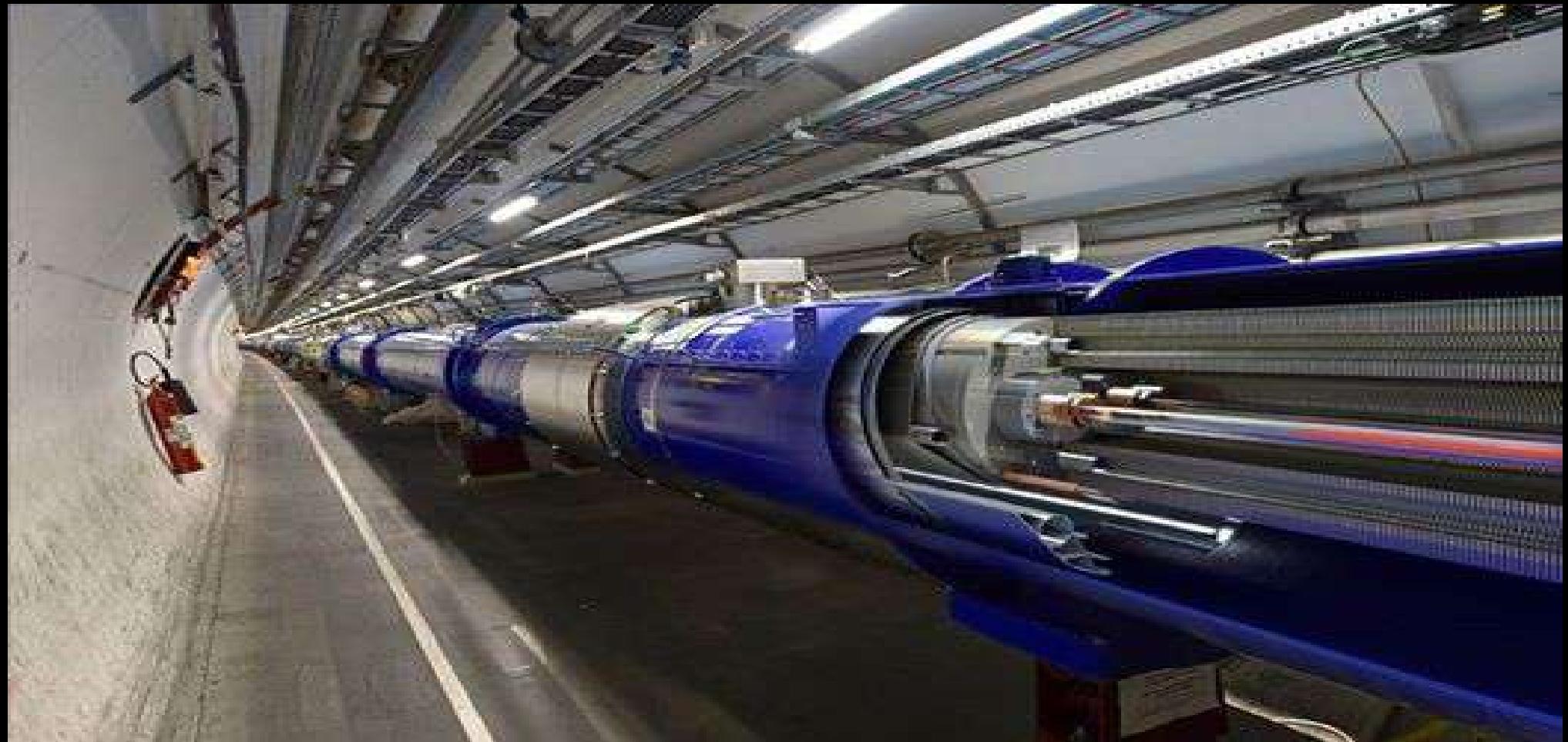
Physics Letters B 756 (2016) 345–349



# Invisible Higgs decays

Joshipura & J.V.

Nucl.Phys. B397 (1993) 105-122



Higgs searches

Bonilla Fonseca & J.V. Phys.Lett. B756 (2016) 345-349 ...

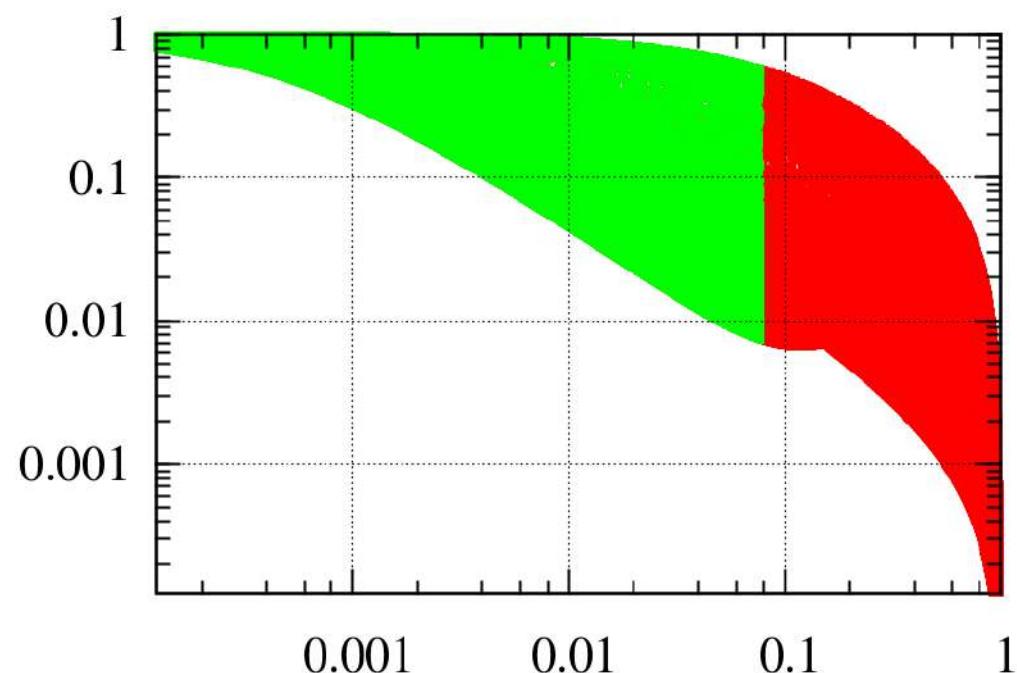
# Neutrino mass and invisible Higgs decays at the LHC

Cesar Bonilla,<sup>1,\*</sup> Jorge C. Romão,<sup>2,†</sup> and José W. F. Valle<sup>1,‡</sup>

$v_\sigma = 3 \text{ TeV}$

channel	ATLAS	CMS
$\mu_{\gamma\gamma}$	$1.17 \pm 0.27$	$1.14^{+0.26}_{-0.23}$
$\mu_{WW}$	$1.00^{+0.32}_{-0.29}$	$0.83 \pm 0.21$
$\mu_{ZZ}$	$1.44^{+0.40}_{-0.35}$	$1.00 \pm 0.29$
$\mu_{\tau^+\tau^-}$	$1.4^{+0.5}_{-0.4}$	$0.91 \pm 0.27$
$\mu_{b\bar{b}}$	$0.2^{+0.7}_{-0.6}$	$0.93 \pm 0.49$

$\text{BR}(H_2 \rightarrow \text{Inv})$

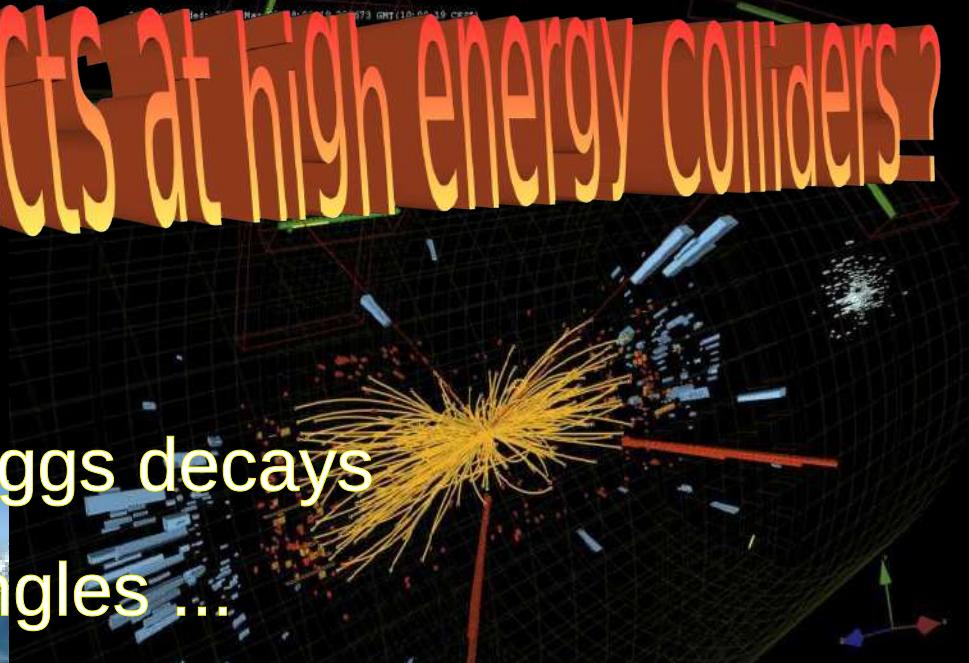


$H_i \rightarrow JJ$  and  $H_2 \rightarrow 2H_1 \rightarrow 4J$

$\left( \text{when } m_{H_1} < \frac{m_{H_2}}{2} \right).$

# Neutrino effects at high energy colliders?

- probe neutrino messengers
- probe e-weak breaking e.g. Higgs decays
- re-measure neutrino mixing angles ...

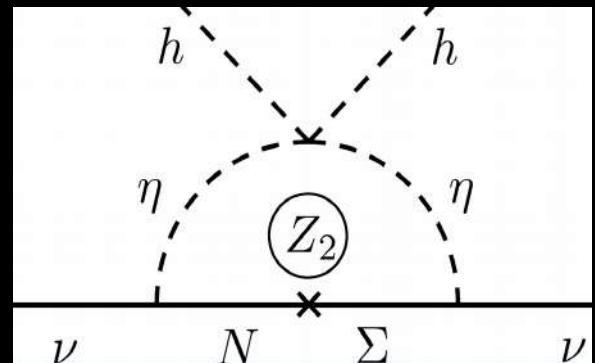


Theories of neutrino as  
attractive EW breaking benchmarks



they can hold the key  
to Dark matter problem

Even if neutrinos form only  
tiny DM fraction



# scotogenic dark matter

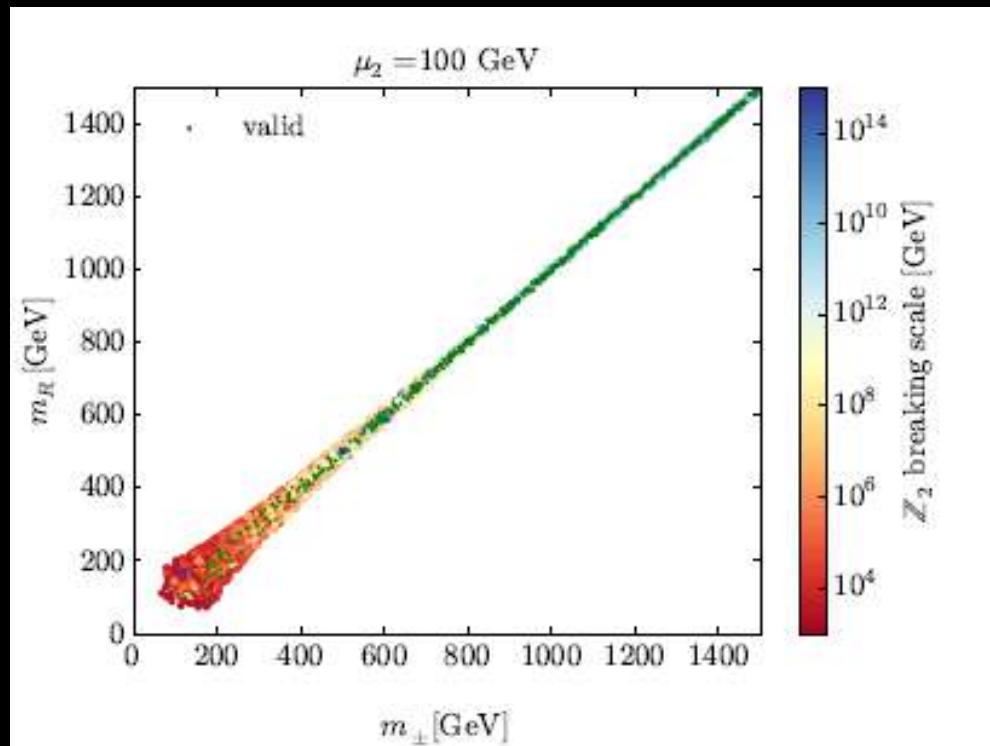
E Ma, Hirsch et al JHEP 1310 (2013) 149

	Standard Model			Fermions		Scalars	
	$L$	$e$	$\phi$	$\Sigma$	$N$	$\eta$	$\Omega$
Generations	3	3	1	1	1	1	1
$SU(2)_L$	2	1	2	3	1	2	3
$U(1)_Y$	-1/2	-1	1/2	0	0	1/2	0
$Z_2$	+	+	+	-	-	-	+

WIMP dark Matter as radiative neutrino mass messenger

Merle et al JHEP 1607 (2016) 013

Either scalar or fermion messenger  
“susy” without susy



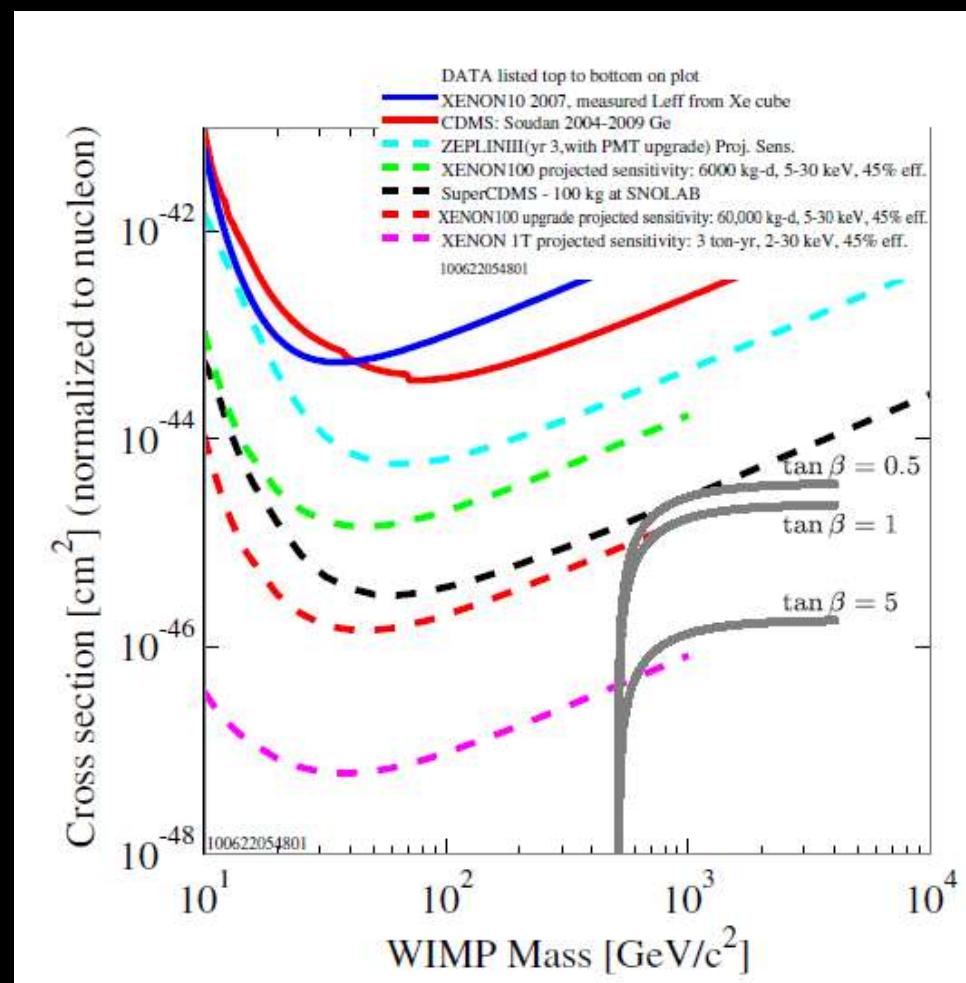
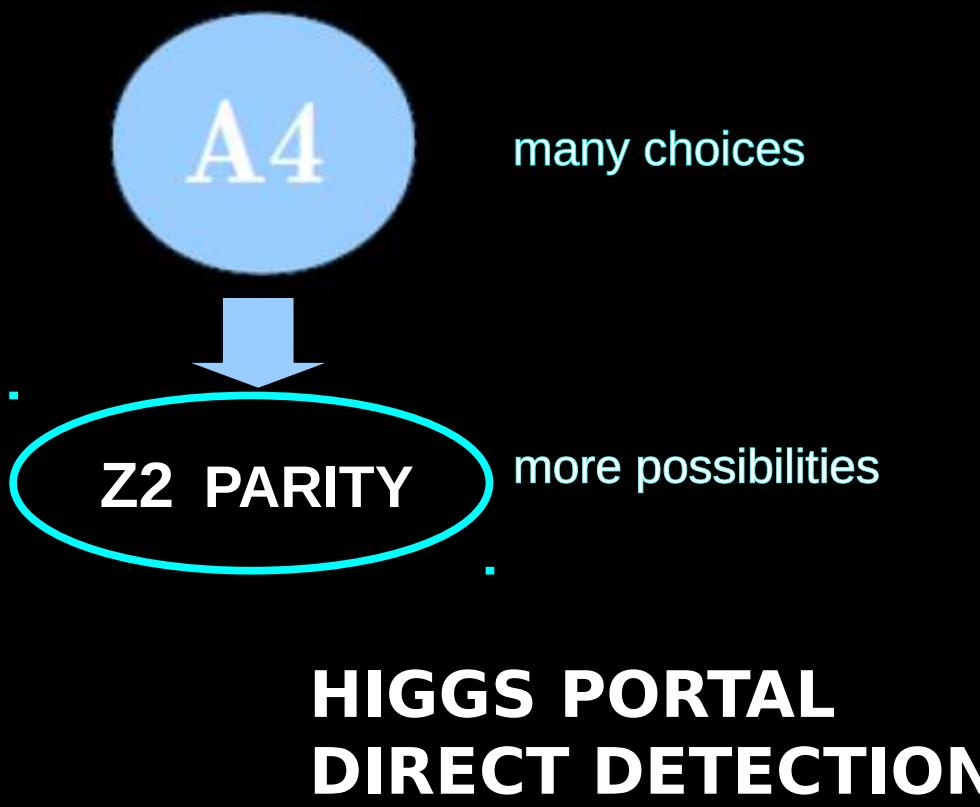
# DARK MATTER FROM FLAVOR SYMMETRY

- *Accidental?*

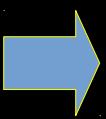
Lavoura, Morisi, JV JHEP 1302(2013) 118

- *unbroken subgroup*

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



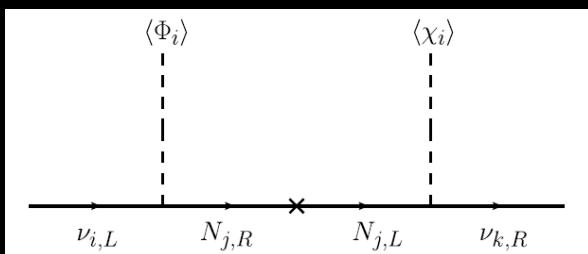
Fields	$Z_4$	$Z_2$	Fields	$Z_4$	$Z_2$
$\bar{L}_{i,L}$	$\mathbf{z}^3$	1	$\nu_{i,R}$	$\mathbf{z}$	-1
$l_{i,R}$	$\mathbf{z}$	1	$\bar{N}_{i,L}$	$\mathbf{z}^3$	1
$N_{i,R}$	$\mathbf{z}$	1			
$\Phi$	1	1	$\chi$	1	-1
$\zeta$	$\mathbf{z}$	1	$\eta$	$\mathbf{z}^2$	1



Chiulia et al

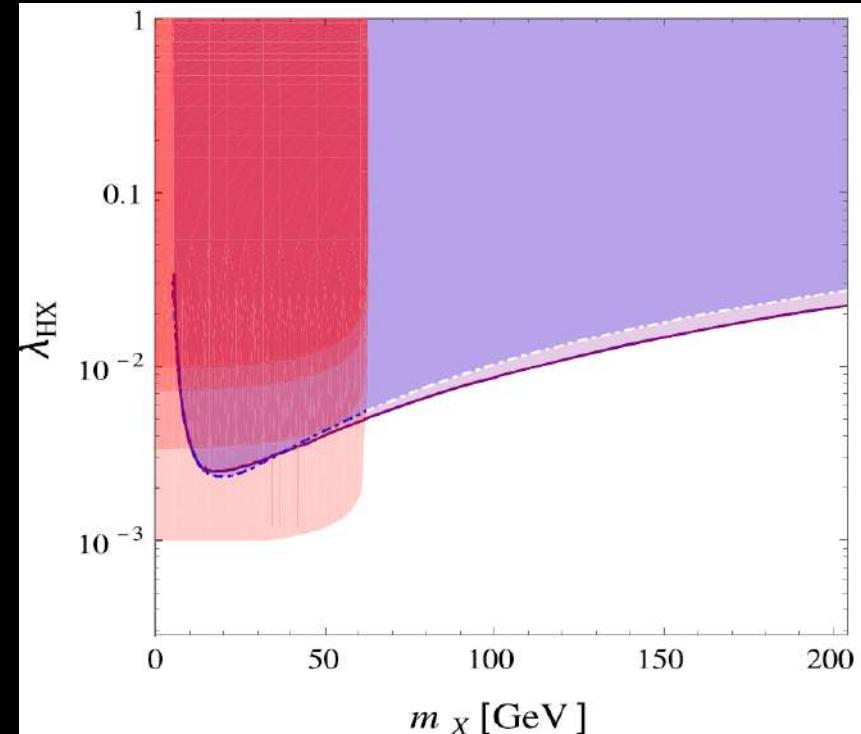
arXiv:1606.04543

Phys.Lett. B761 (2016) 431



# DM Stability from Diracness

# non-SUSY Wimp



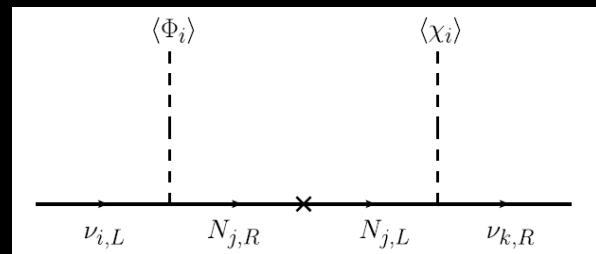
No neutrinoless  $\beta\beta$  decay

Search for neutrinoless quadruple- $\beta$  decay

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

Fields	$SU(2)_L$	$A_4$	$Z_4$	Fields	$SU(2)_L$	$A_4$	$Z_4$
$\bar{L}_i$	2	3	$z^3$	$\nu_{e,R}$	1	1	$z$
$\bar{N}_{i,L}$	1	3	$z^3$	$\nu_{\mu,R}$	1	$1'$	$z$
$N_{i,R}$	1	3	$z$	$\nu_{\tau,R}$	1	$1''$	$z$
$l_{i,R}$	1	3	$z$	$d_{i,R}$	1	3	$z$
$\bar{Q}_{i,L}$	2	3	$z^3$	$u_{i,R}$	1	3	$z$
$\Phi_1^u$	2	1	1	$\chi_i$	1	3	1
$\Phi_2^u$	2	$1'$	1	$\eta$	1	1	$z^2$
$\Phi_3^u$	2	$1''$	1	$\zeta$	1	1	$z$
$\Phi_i^d$	2	3	1				

Chiulia et al  
<http://inspirehep.net/record/1602168>



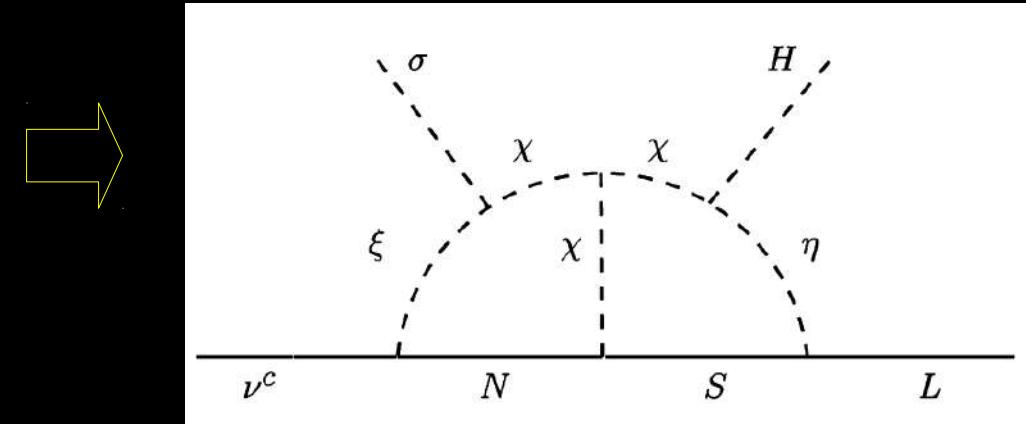
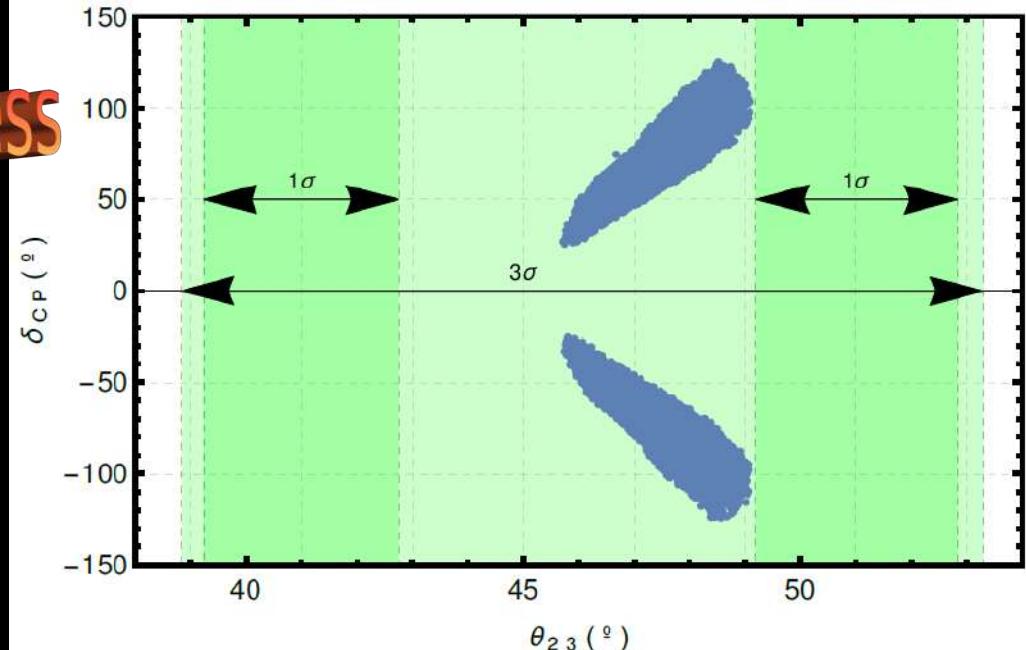
# DM Stability from Diracness non SUSY Wimp

C. Bonilla et al. / Physics Letters B 762 (2016) 214–218

**Table 1**

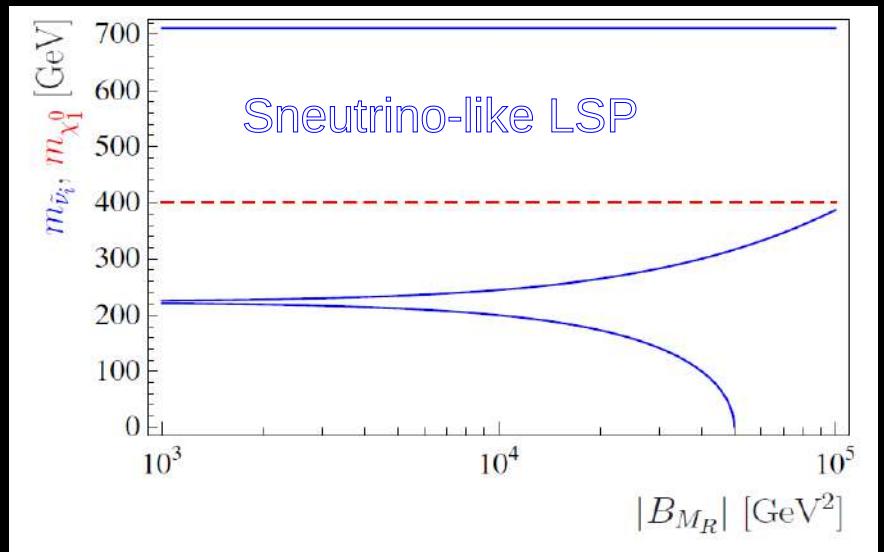
Relevant particle content and quantum numbers of the model.

	$\bar{L}$	$v^c$	$H$	$\eta$	$N$	$S$	$\sigma$	$\xi$	$\chi$
$SU(2)_L$	2	1	2	2	1	1	1	1	1
$U(1)_D$	-1	3	0	0	-1	1	2	-2	0
$Z_3^{DM}$	1	1	1	$\alpha$	$\alpha$	$\alpha$	1	$\alpha^2$	$\alpha$
$Z_3$	$\omega$	$\omega^2$	1	1	$\omega$	$\omega^2$	1	1	1



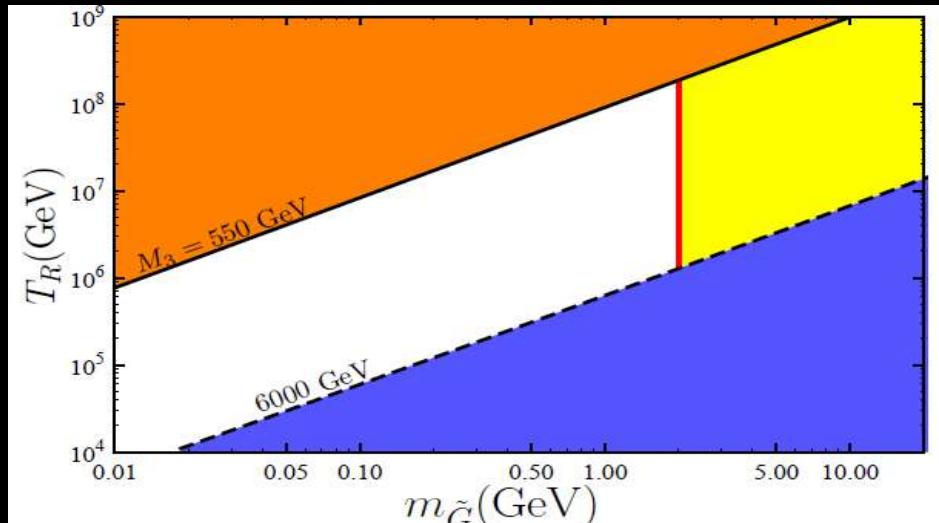
# SUSY WIMP dark matter

Arina et al PRL101 (2008) 161802  
Bazzocchi, Cerdeno, Munoz, J.V., PRD81 (2010) 051701  
De Romeri, Hirsch, JHEP 1212 (2012) 106



susy inverse seesaw ...

Restrepo et al PRD85 (2012) 023523



# decaying Gravitino dark matter

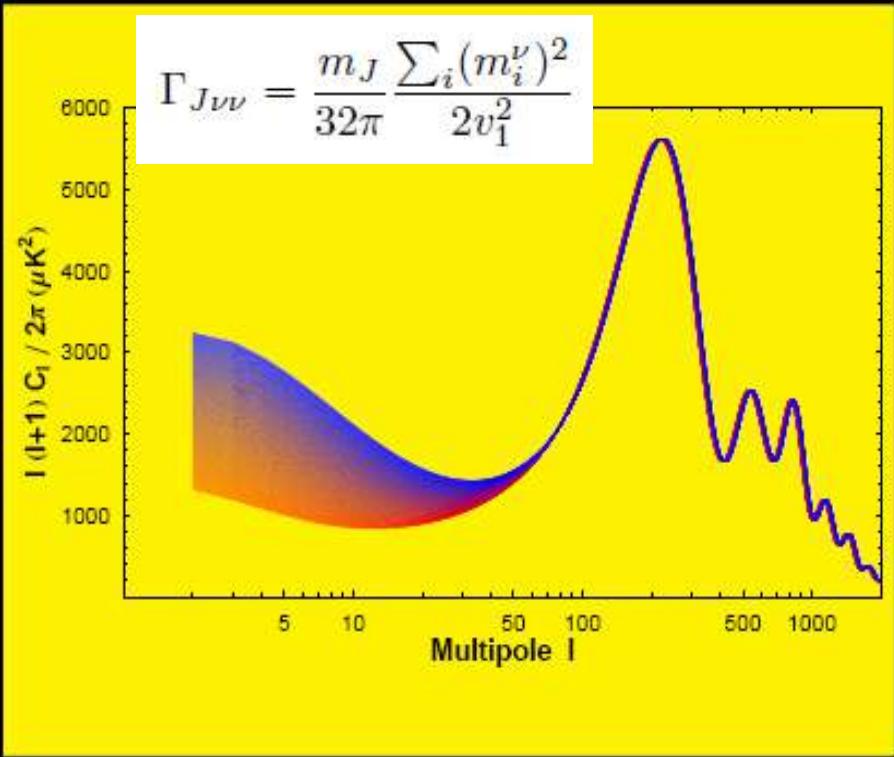
doubly suppressed decays

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

chosen to fit neutrino osc. data

# Consistency with CMB

Lattanzi & Valle, PRL99 (2007) 121301

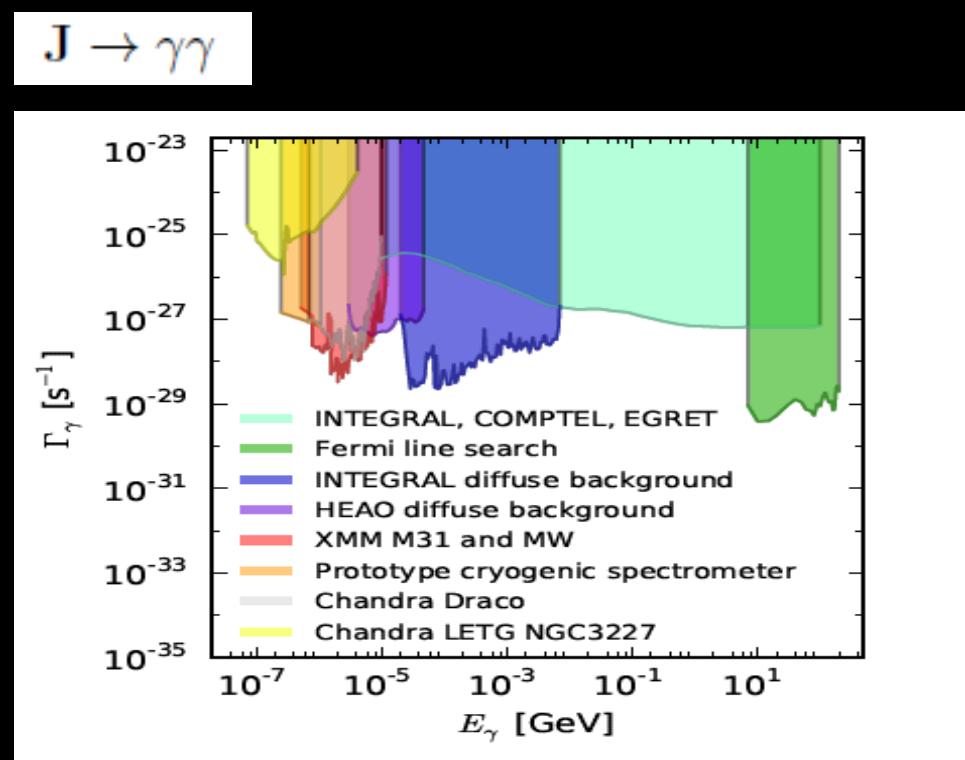


Bazzocchi & al JCAP 0808 (2008) 013

Esteves et al, PRD 82, 073008 (2010)

dark matter majorons

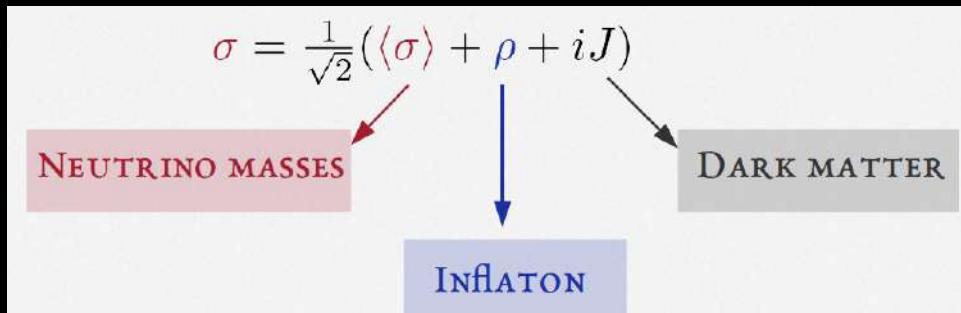
Berezinsky, Valle PLB318 (1993) 360



Lattanzi et al PRD88 (2013) 063528

# Majoron dark matter & seesaw inflation

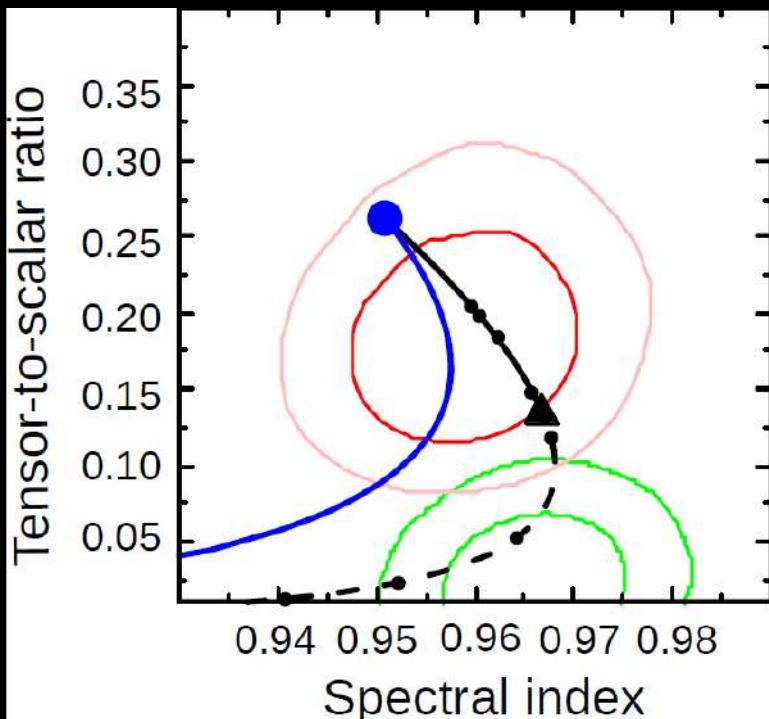
Boucenna, Morisi, Shafi, Valle  
PRD90 (2014) 055023



type-I seesaw **Leptogenesis**

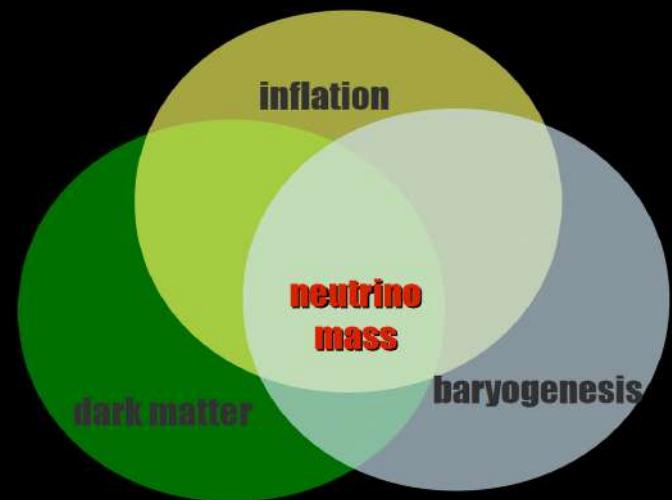
Aristizabal et al JCAP 1407 (2014) 052

Quartic versus Higgs Inflation

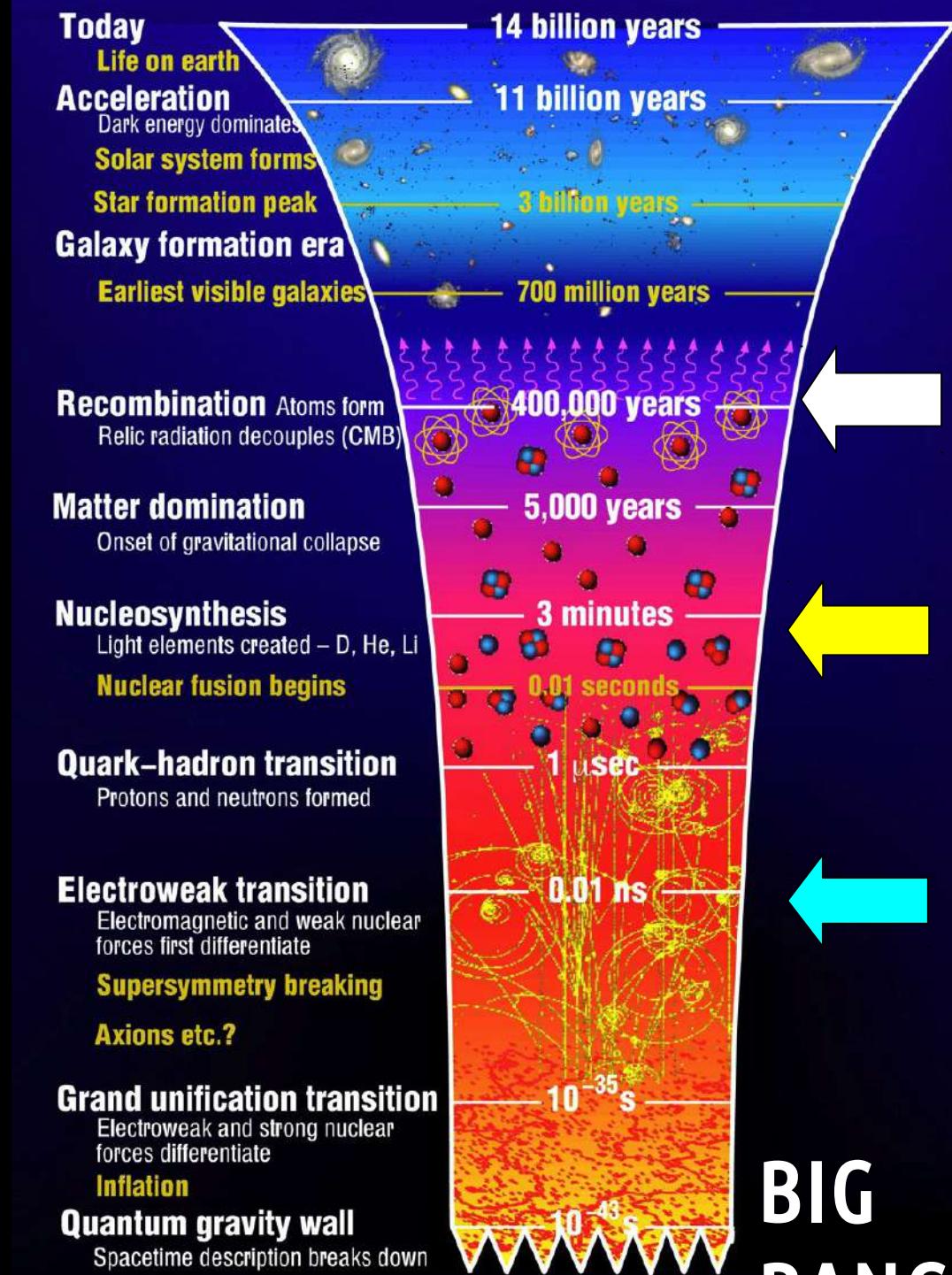


<http://arxiv.org/pdf/1502.00612v1>

neutrinos may explain DM through an emergent theory ...



new features  
& phenomena

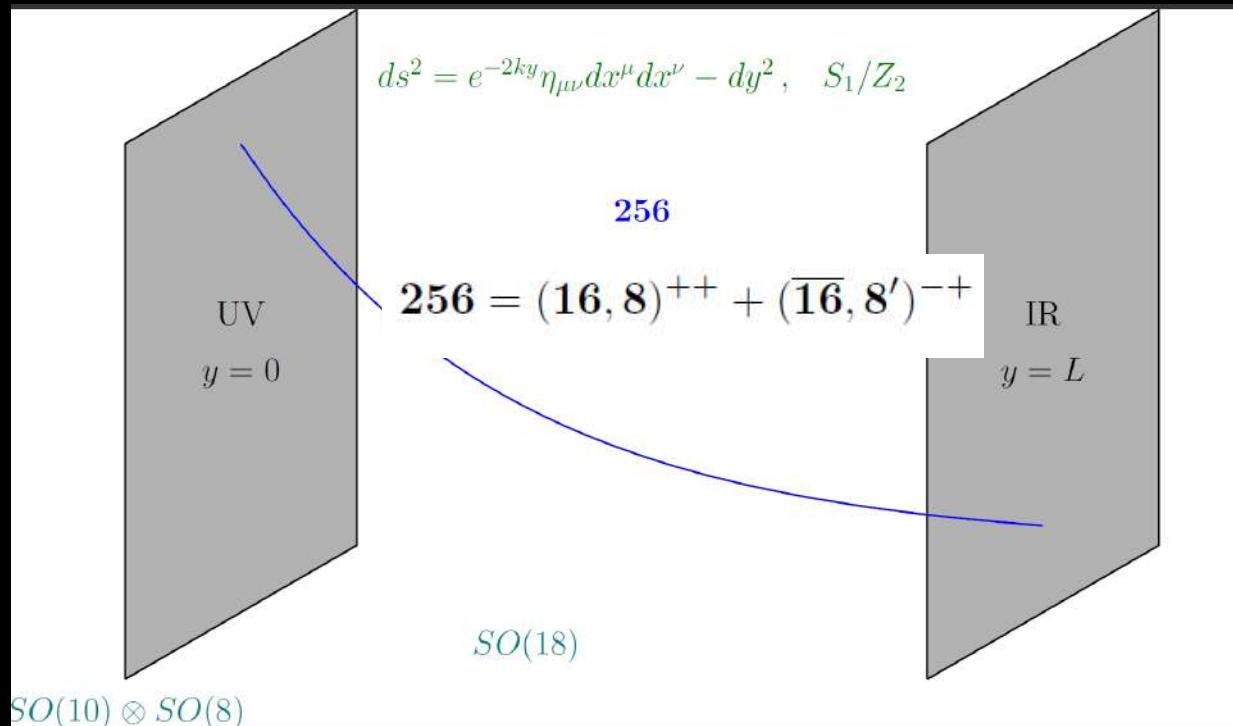


BIG  
BANG

# Comprehensive unification

<http://arxiv.org/abs/arXiv:1706.03116>

forces + families : recent revival  
of an old idea



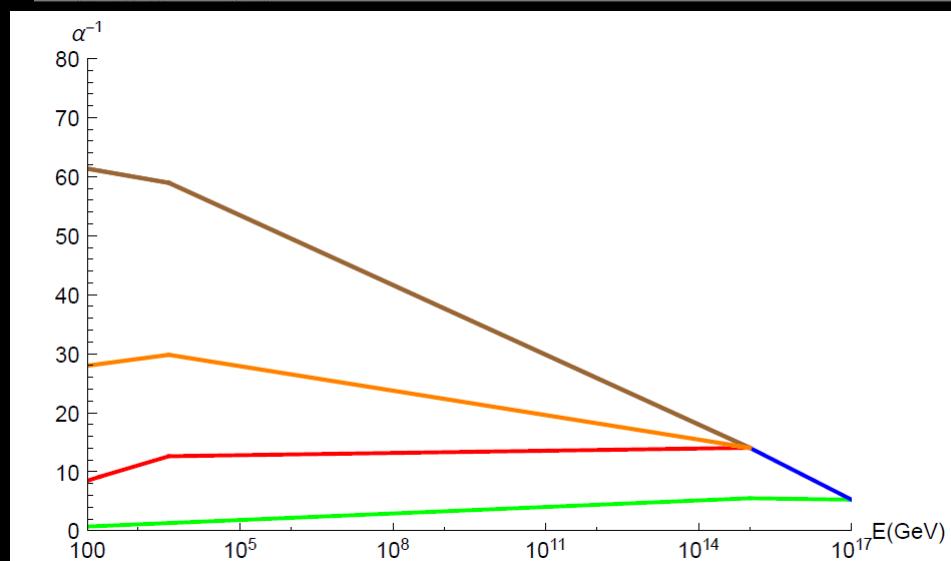
Wilczek & Zee  
Gellman Ramond Slansky

$$\begin{aligned} \mathbf{16} \rightarrow & (\mathbf{3}, \mathbf{2}, 1/6) + (\mathbf{1}, \mathbf{2}, -1/2) + (\bar{\mathbf{3}}, \mathbf{1}, 1/3) \\ & + (\bar{\mathbf{3}}, \mathbf{1}, -2/3) + (\mathbf{1}, \mathbf{1}, 1) + \boxed{(\mathbf{1}, \mathbf{1}, 0)}, \end{aligned}$$

$SO(2n + 2m)$  spinors split as

$$\begin{aligned} \mathbf{2}^{n+m-1} &\rightarrow 2^m \times \mathbf{2}^{n-1} \\ SO(2n + 2m) &\rightarrow SO(2n) \end{aligned}$$

Chirality problem



Promote  $M_4$  to  $AdS_5$

Use orbifold breaking mechanism to decouple mirror families  
They become heavy Kaluza-Klein modes

$$SO(10) \times SO(8) \rightarrow SO(10) \times SO(5)_{HC}$$

Figure:  $SO(5)_{HC}$  gauge coupling (green line) in addition to the SM couplings (red, orange and brown lines).

neutrinos not only  
first manifestation  
of new physics

also may indicate the path  
to what is the new physics