Neutrinos as a probe of New Physics effects

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Searching for New Physics

Neutrino oscillation physics is entering a precision era:

- Good knowledge of mixing angles and mass differences
- First hints of a non-vanishing CP phase
- Sum of the neutrino masses bounded from above

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It is time to devote serious efforts to the search of New Physics in the lepton sector, using neutrinos

Two (three) different items

Main message of this talk:

Neutrinos can be used as probes for some New Physics scenarios

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New research field in theoretical particle physics

Not discussing new results in details, only two examples to show how New Physics shows up in the ν sector

- Sterile neutrinos
- Large Extra Dimensions
- (Non Standard Interactions)

Standard neutrino oscillations

- Neutrinos can also be described in terms of mass eigenstates ν_i

neutrino matrix

matrix

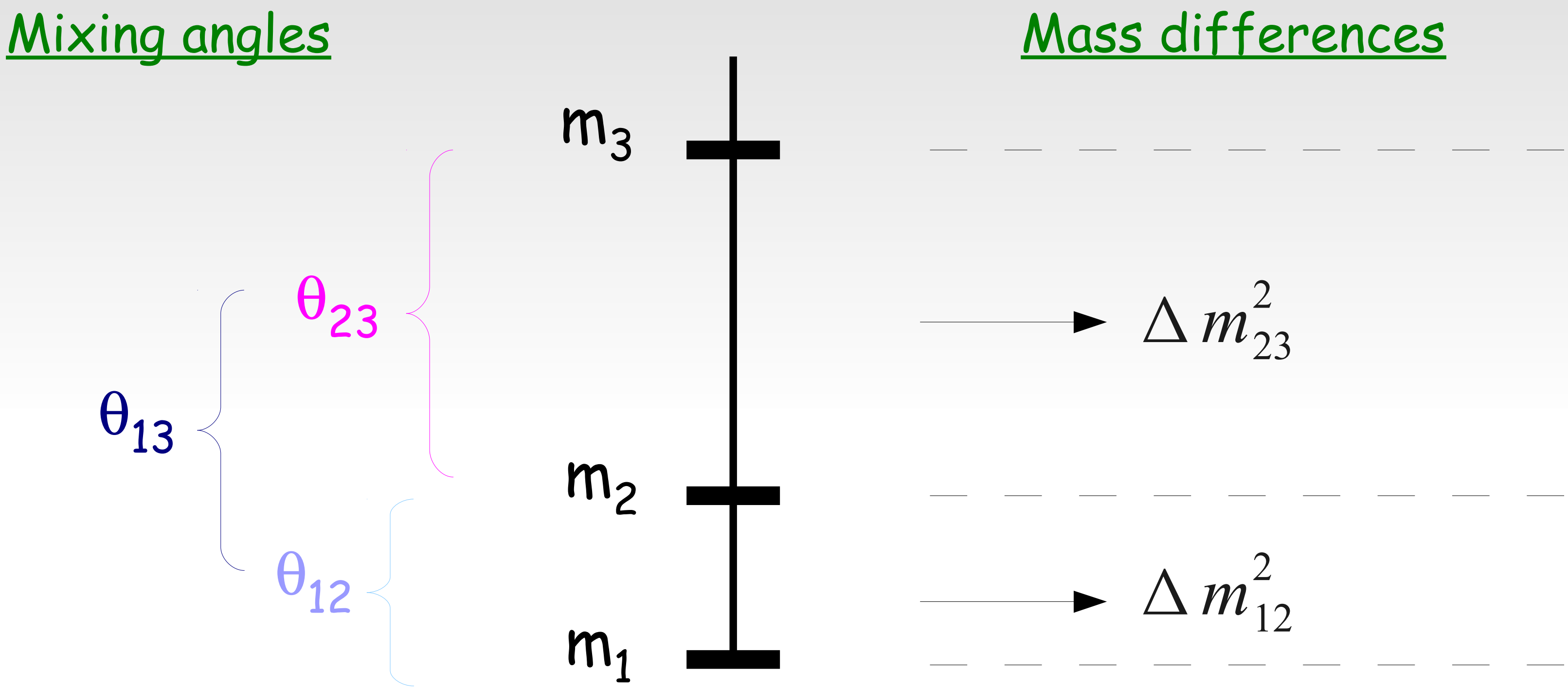
$$|\nu_\alpha\rangle = \Sigma_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$$

- Considering time evolutions of mass eigenstates:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t)\rangle|^2 = \left| \Sigma_j U_{\beta j} U^*_{\alpha j} e^{\frac{-i m_j^2 L}{2 E_\nu}} \right|^2$$

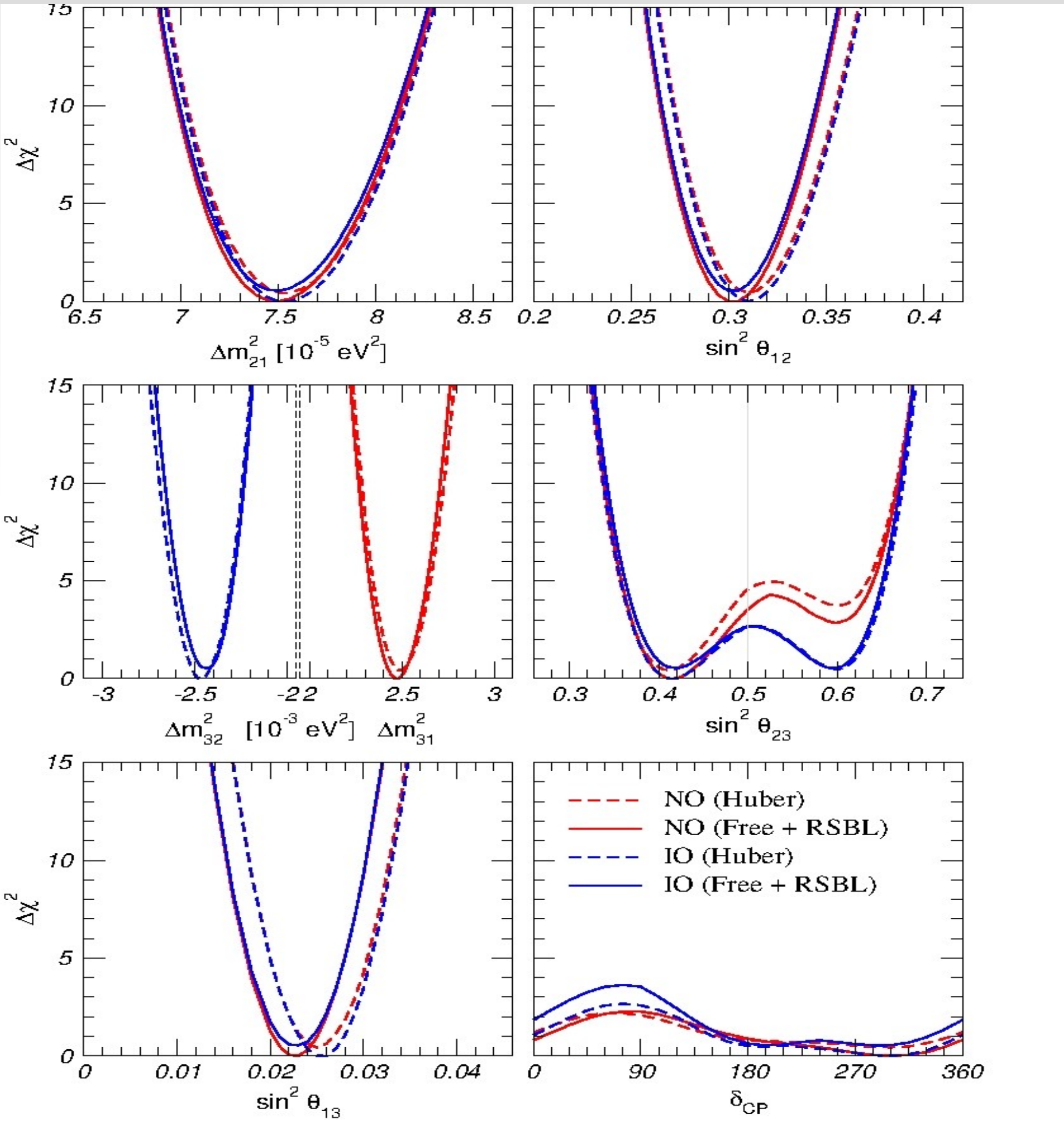
$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{atmospheric\ \ mixing} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{reactor\ \ mixing} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{solar\ \ mixing}$$

To be determined by oscillation experiments



- And: a possible CP phase δ and the absolute order of the mass eigenstates (normal or inverted hierarchy)

Summary of the experimental results



Gonzalez-Garcia et al. JHEP1212,(2012)123

Parameter	Fit results
θ_{12}	$33.36^{+0.81}_{-0.78}$
θ_{13}	$8.66^{+0.44}_{-0.46}$
θ_{23}	$40.0^{+2-1}_{-1.5}$
δ (?)	300^{+66}_{-138}
Δm^2_{23} (10^{-3} eV^2)	$2.47^{+0.07}_{-0.07}$
Δm^2_{12} (10^{-5} eV^2)	$7.50^{+0.18}_{-0.19}$

- precision era in the determination of mixing parameters

Perturbative approach

- $\sin^2 2\theta_{13}$ is a small parameter

↓

- New effects in oscillations must be even smaller

$$A(\nu_\alpha \to \nu_\beta) = A^{SM}\underbrace{(\nu_\alpha \to \nu_\beta) + \delta A_{\alpha\beta}}_{\text{interference}}$$

From the interference term one can:
(δ^2 is generally too small)

- set strong bounds on δ if the data are precise and very well described by SM physics
- "measure" δ if the data are precise and NOT well described by SM physics

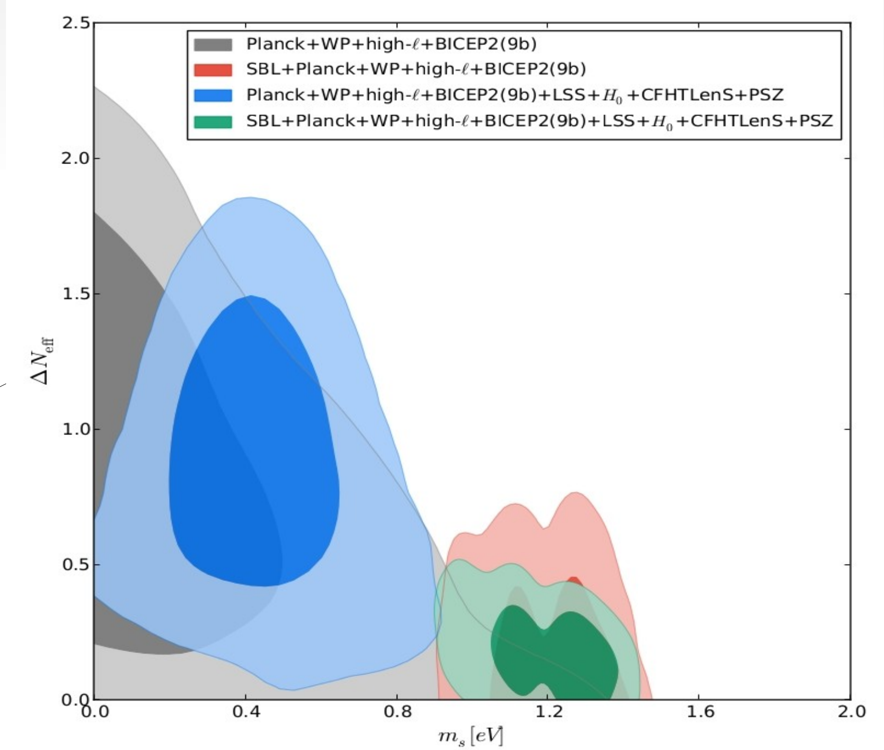
Ex: $\sin^2 2\theta^{eff}_{13} = \sin^2 2\theta^{SM}_{13}\ (1+\delta)$

The case of sterile neutrinos

- The number of active neutrino species is fixed by the Z-boson invisible decay width: $N_\nu = 2.994 \pm 0.011$
- Extra families (if they exist) must have either very heavy neutrinos ($m_N > m_Z/2$), or no neutrinos at all

Standard Model singlets allowed: sterile neutrinos

M.Archidiacono et al., arXiv:1404.1794 [astro-ph.CO]

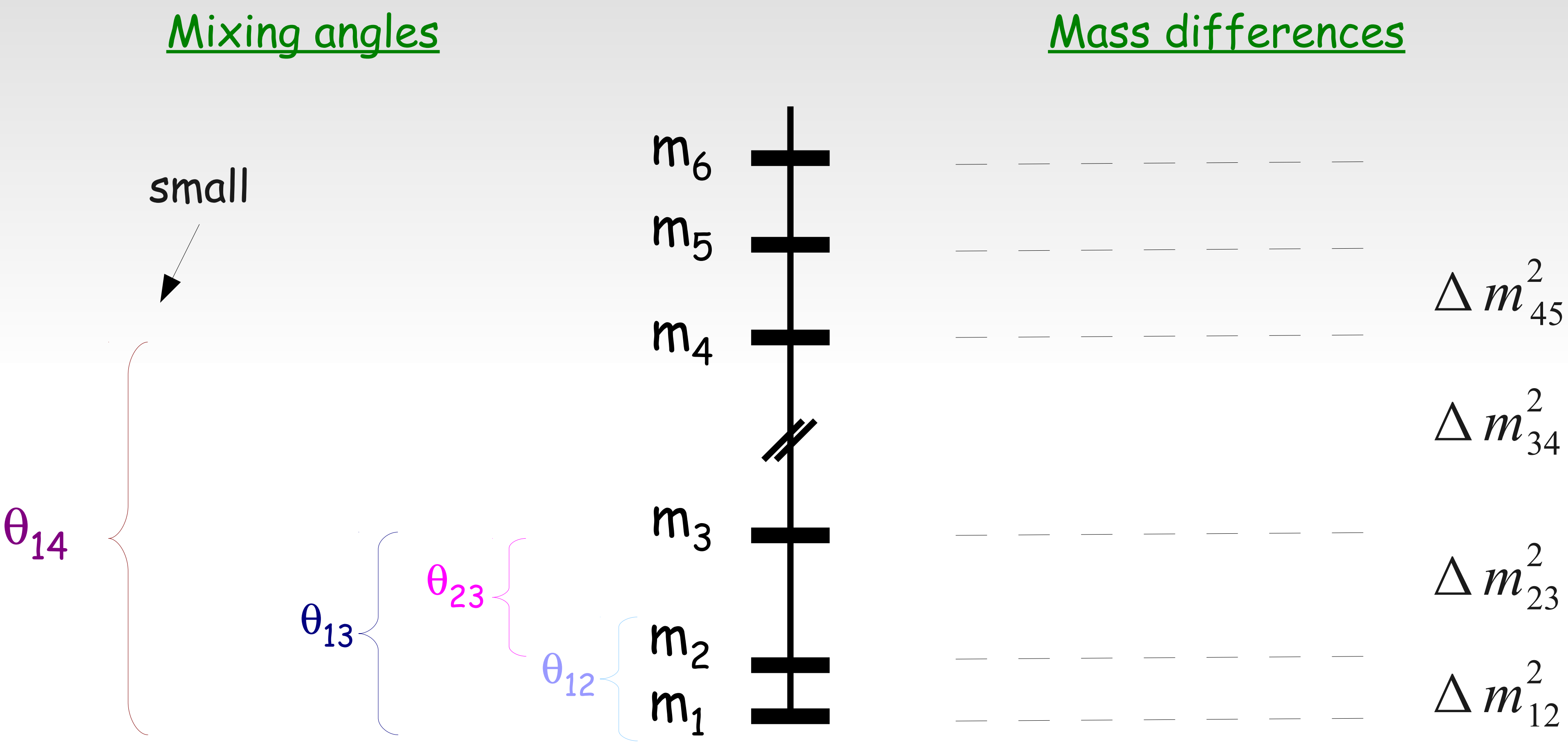


extra species

Mass of the extra species

Renewed interest after the recent BICEP2 results

The case of sterile neutrinos



The case of sterile neutrinos

$$U = \underbrace{R_{34}\,R_{24}\,R_{14}}_{\text{perturbations}}\,R_{23}\,R_{13}\,R_{12}$$

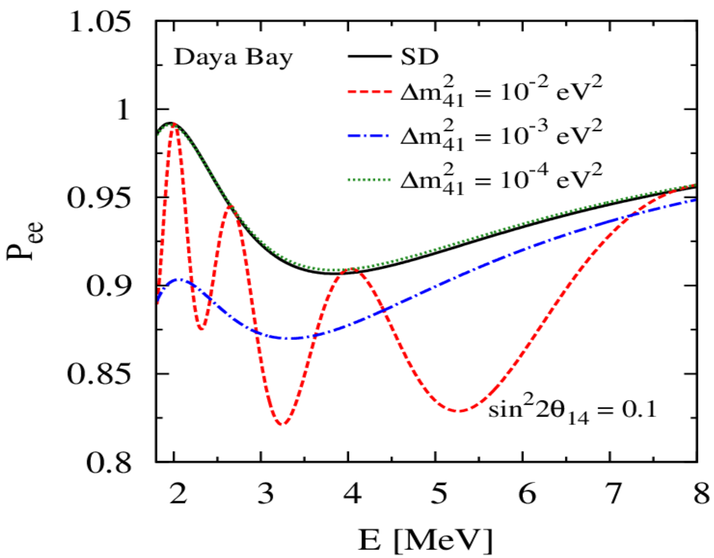
Example: $\nu_e \rightarrow \nu_e$ transition

$$P_{ee} \sim 1 - s_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{32}^2 L}{4E_\nu}\right) - c_{12}^2\ \sin^2 2\theta_{13}\ \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) \Rightarrow \text{Standard}$$

$$- s_{12}\sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m_{42}^2 L}{4E_\nu}\right) - c_{12}^2\ \sin^2 2\theta_{14}\ \sin^2\left(\frac{\Delta m_{41}^2 L}{4E_\nu}\right) \Rightarrow \text{Interference}$$

Current upper limit:
$\sin^2 2\theta_{14} \sim 0.1$

M.C.Gonzalez-Garcia et al.,
JHEP 1212, 123 (2012)



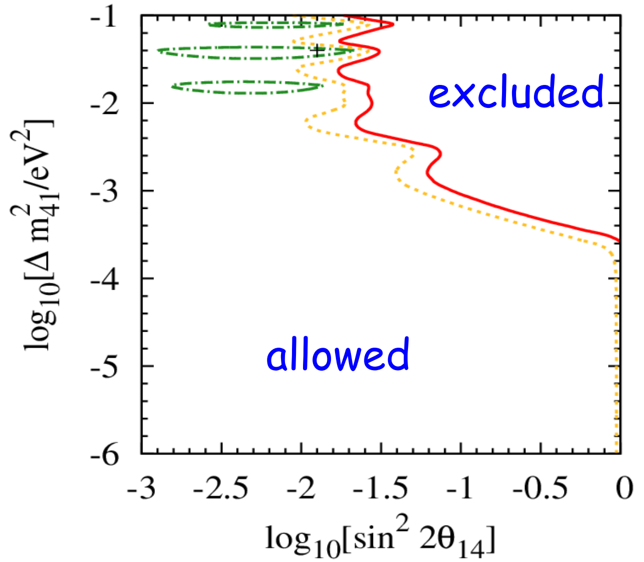
The case of sterile neutrinos

Bounds on new parameters require experiments
with very low systematic uncertainties

Daya Bay in China:
$\bar{\nu}_e \to \bar{\nu}_e$ transition

neutrinos from reactor plants

1,2 and 3σ confidence level



$\sin^2 2\theta_{14} <\sim 10^{-2}$

I.Girardi, D.Meloni, T.Ohlsson, H.Zhang and S.Zhou, arXiv:1405.6540 [hep-ph].

Large Extra Dimensions

Hierarchy problem:

there exist two fundamental energy scales:

- the electroweak scale $M_D \sim 1$ TeV
- quantum gravity $M_{PL} \sim 10^{18}$ GeV

A possible way-out:

- there are δ compact extra dimensions of radius R and M_D is the only fundamental energy scale: $M^2_{PL} = R^\delta M^{\delta+2}_D$
- at distances less than R gravity propagates in all $4+\delta$ dimensions
- Standard Model fields are confined in our 4D world

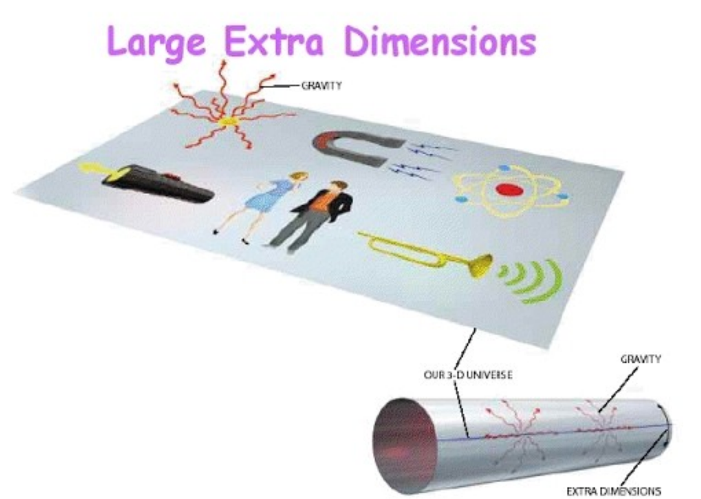
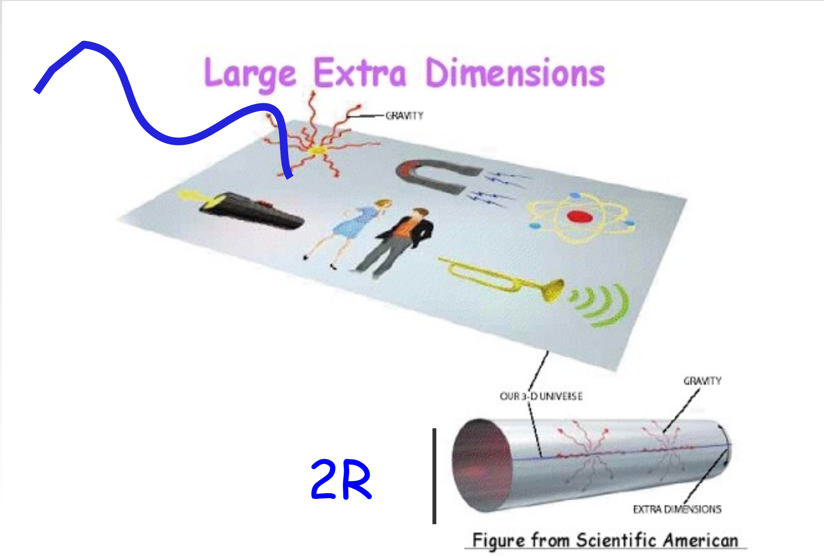


Figure from Scientific American

Right-handed neutrinos in extra dimensions

Since neutrinos are special: massless right-handed neutrinos ν_R also feel the whole 5D space

- ν_R propagated in the whole 5D
- $\nu_R = \nu_R(x^\mu, y)$



Imposing $y = y + 2\pi R$ on the ν_R wave function generates infinite replica of the field

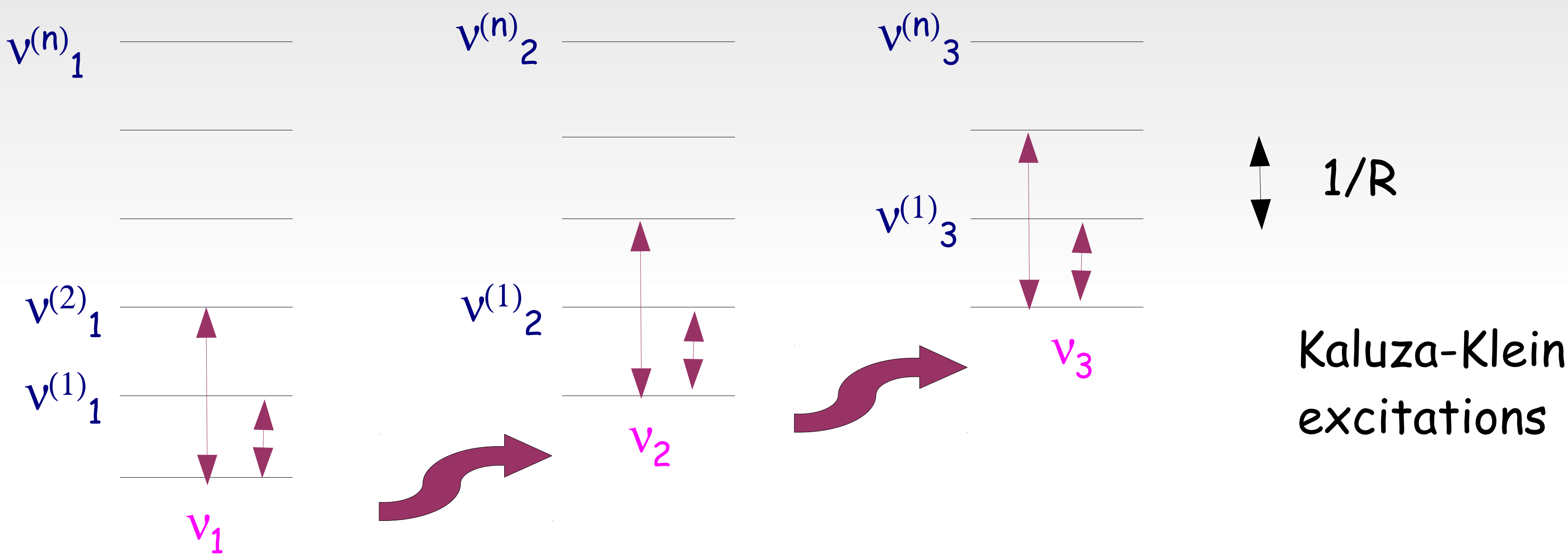
$$\nu_R(x, y) \sim \Sigma_{n=-\infty}^{+\infty} \nu_R^{(n)}(x, y)\, e^{\frac{i n y}{R}}$$

Interaction term:

$$\lambda_{\alpha\beta}\, \nu_L^{\alpha}(x)\, \nu_R^{\beta}(x, 0)\, H(x)$$

Right-handed neutrinos in extra dimensions

For the mass eigenstates (normal ordering):



Oscillations can take place among active-active and active-KK (infinite) states

Right-handed neutrinos in extra dimensions

$$A(\nu_\alpha \to \nu_\beta) = \Sigma_j U_{\beta j} U^*_{\alpha j} e^{\frac{-i m_j^2 L}{2 E_\nu}} \to \Sigma_{j=1}^{3} \Sigma_{k=0}^{\infty} U_{\beta j} U^*_{\alpha j} \left| W_j^{(k)} \right|^2 e^{\frac{-i \lambda_j^{(k)2} L}{2 E_\nu R^2}}$$

D. Davoudiasl, P. Langacker and M. Perelstein, Phys. Rev. D 65, 105015 (2002)

$W_j^{(k)}$ = Transition between zero modes and KK

$\lambda_j^{(k)}$ = absolute neutrino masses

Depend on the lightest absolute neutrino mass m_0 and R

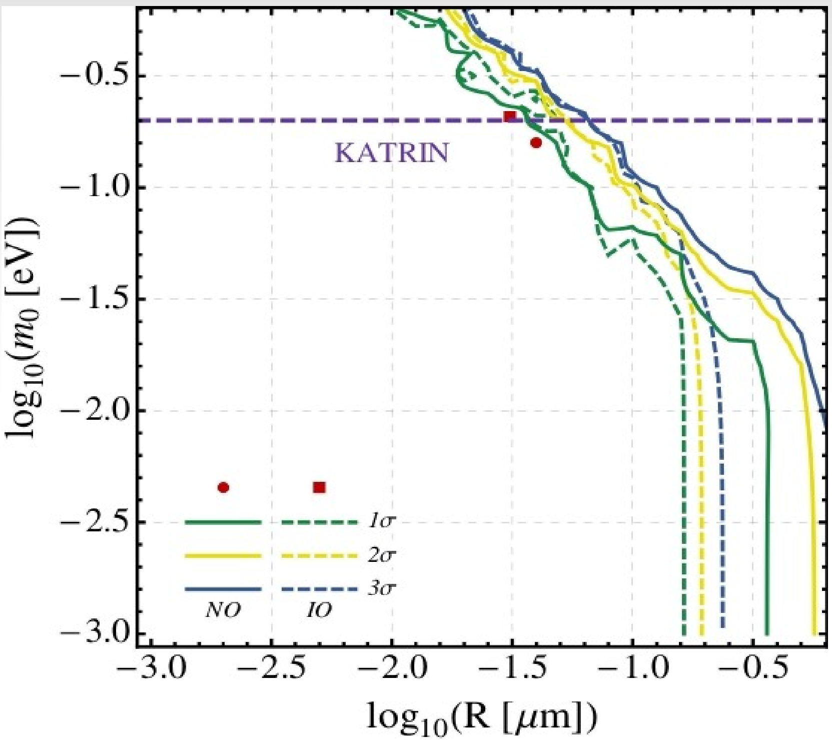
- Only upper limit on m_0 (from $\Sigma_i m_i < 0.2$ eV)
- Limits on R from experiments based on the torsion pendulum:
  $R < 37 \times 10^{-6}$ m (95% CL) or equivalently $M_D > 3.6$ TeV for $\delta=2$ (LHC gives comparable bounds)

J. Beringer et al. (Particle Data Group Collaboration), Phys. Rev. D 86, 010001 (2012)

G.Aad et al. [ATLAS Collaboration], Phys. Rev. Lett.110, 011802 (2013)

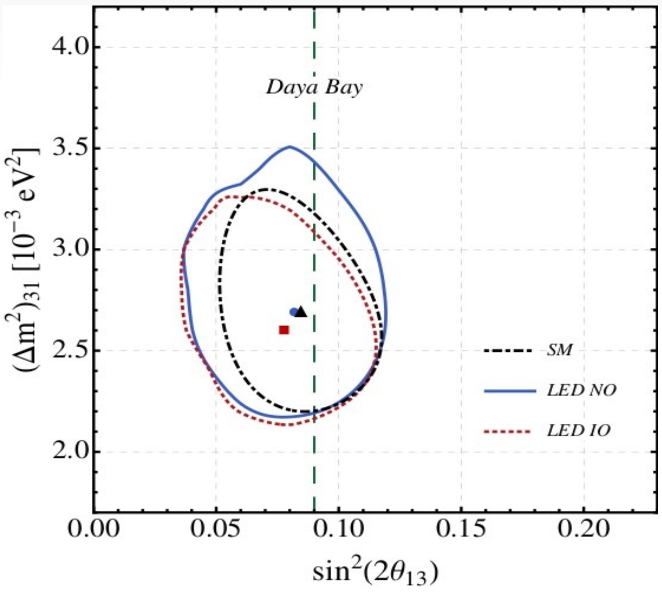
First results...

new limits from Daya Bay



$R < 0.2\ (0.6) \times 10^{-6}$ m @2σ
for Inverted (Normal) Ordering

Effects of New Physics



I. Girardi and D, Meloni, 1403.5507

Conclusions

- Neutrino physics is an active field, from both experimental and theoretical point of views
- Many and precise data are now available, which are very well described in the context of the SM theory of neutrino oscillation
- As for the hadronic sector, New Physics must pop-up as perturbations of the standard picture
- We started to investigate such tiny effects for a variety of New Physics scenarios...

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