A Theoretical Perspective on Neutrinos

26th Lepton Photon

UCSF Mission Bay Conference Center,
San Francisco

27 June 2013

Silvia Pascoli

IPPP - Durham University

Outline

1. Neutrino oscillations and the present status of neutrino physics

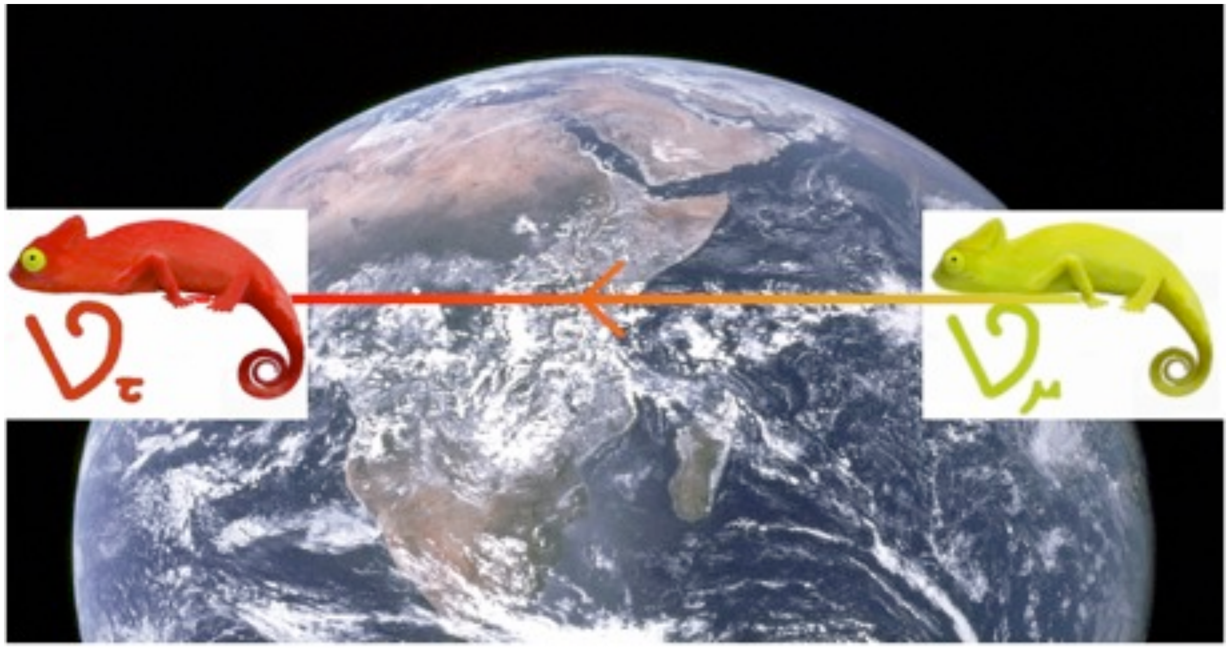
2. Questions for the future: neutrino nature, masses and mixing

3. Neutrino masses beyond the Standard Model: Dirac versus Majorana masses: searching for a new physics scale

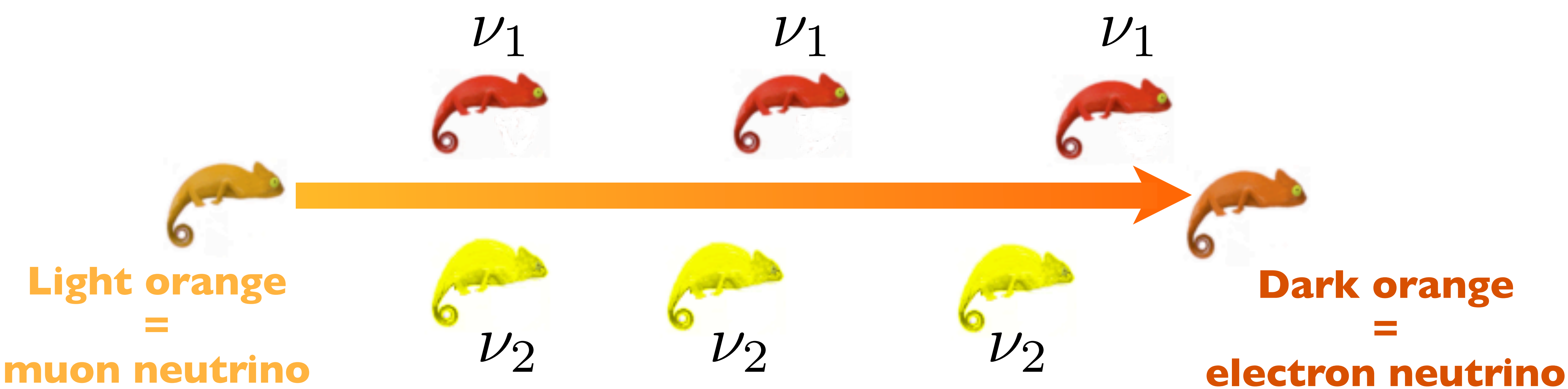
4. The leptonic flavour problem

5. Conclusions

The facts: Neutrinos oscillate



Contrary to what expected in the SM, neutrinos oscillate: after being produced, they can **change their "flavour"**.



A flavour neutrino is a superposition of mass states. If their mass is different, they will evolve in time differently with their superposition corresponding to a different flavour neutrino.

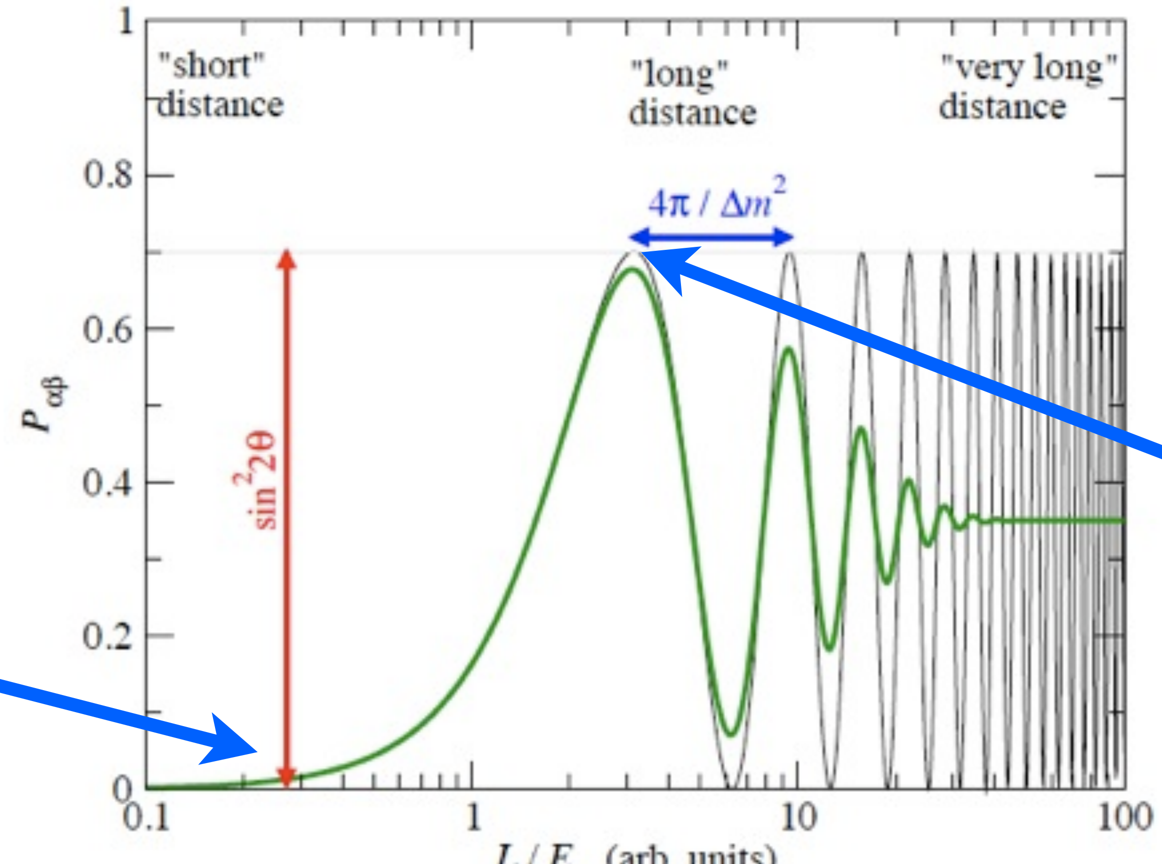
The **probability** for a ν_μ to **transform** into a ν_e at a **distance L** from the source is:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\frac{(m_2^2 - m_1^2)L}{4E}$$

Mixing angle between flavor and mass states

Neutrino masses

At small L no effect



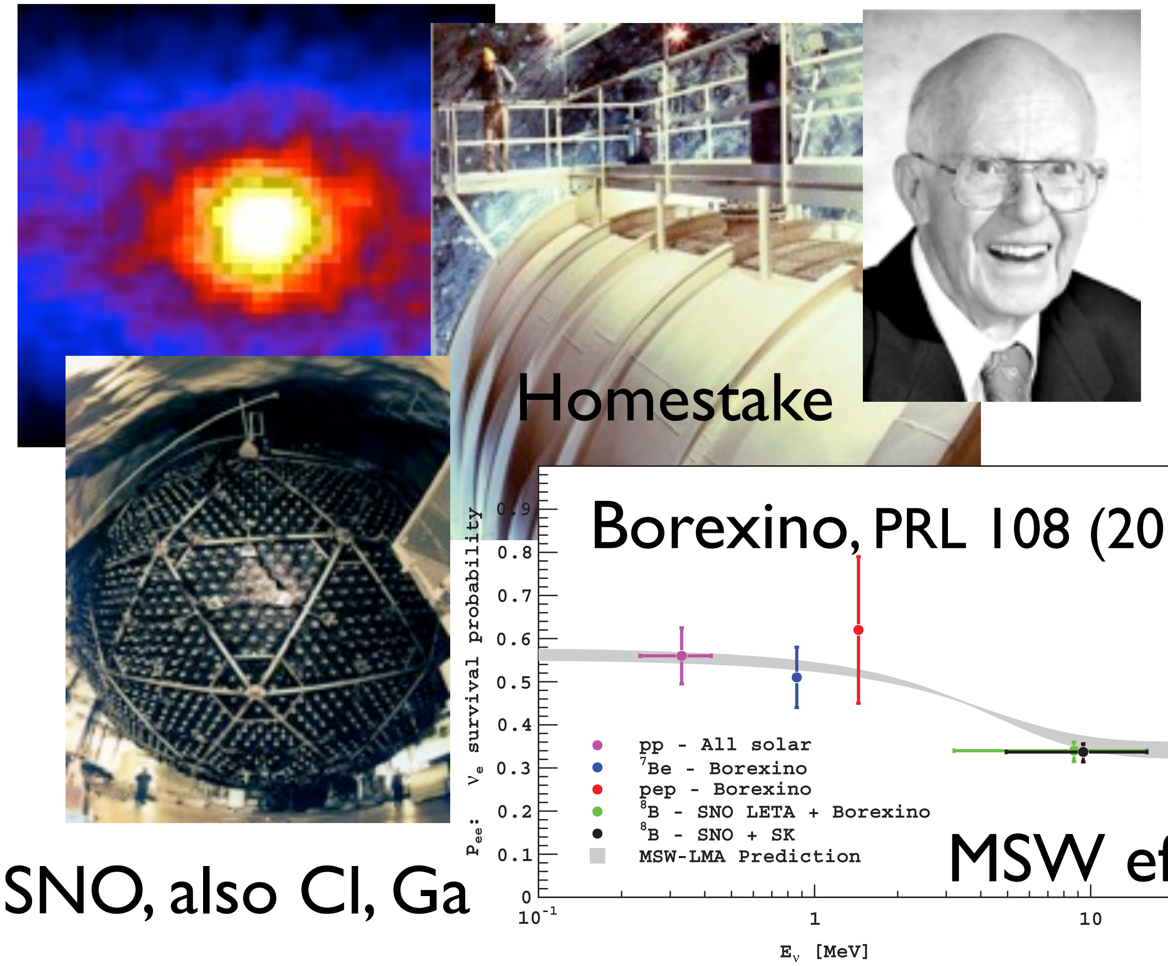
First oscillation maximum

Thanks to T. Schwetz

Neutrino oscillations imply that neutrinos have mass and they mix.
First evidence of physics beyond the SM.

A decade of exciting results

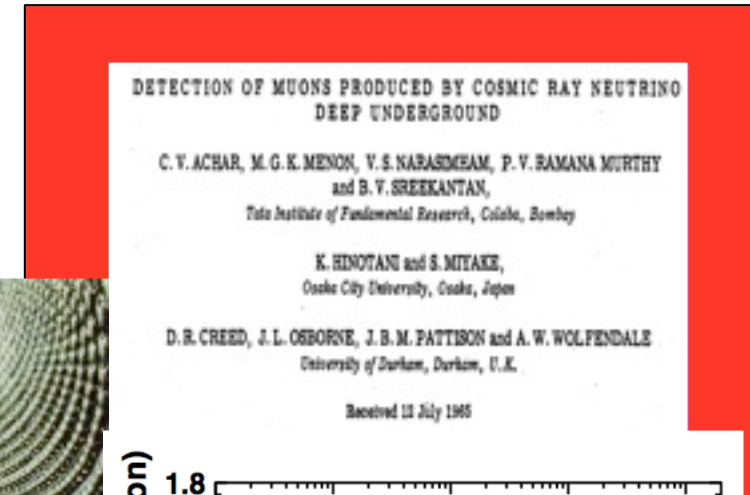
Solar neutrinos



SNO, also Cl, Ga

MSW effect

Atmospheric neutrinos

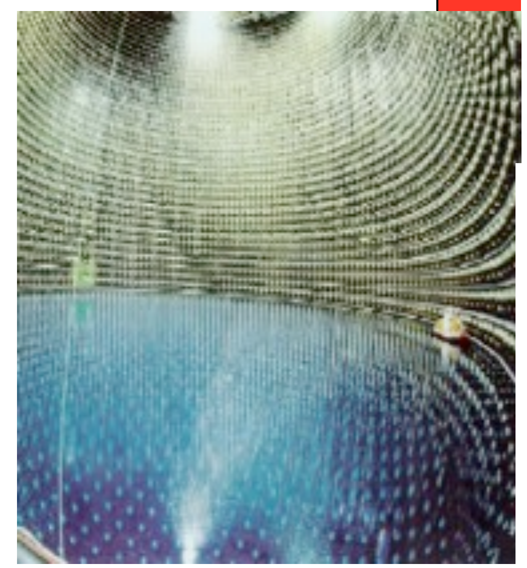

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

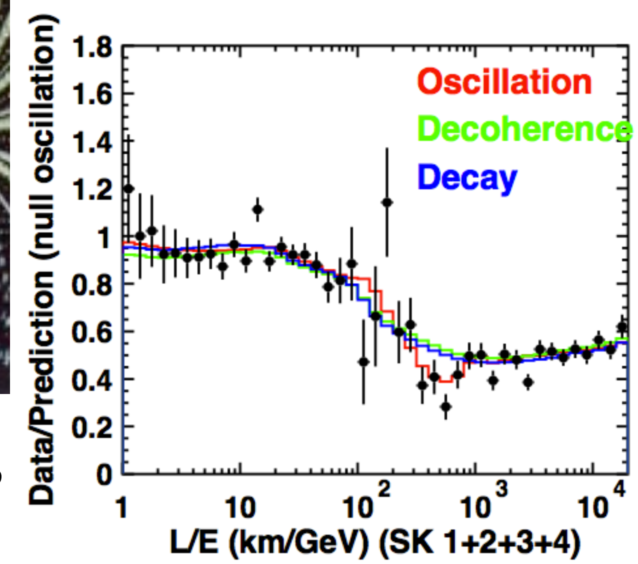
K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

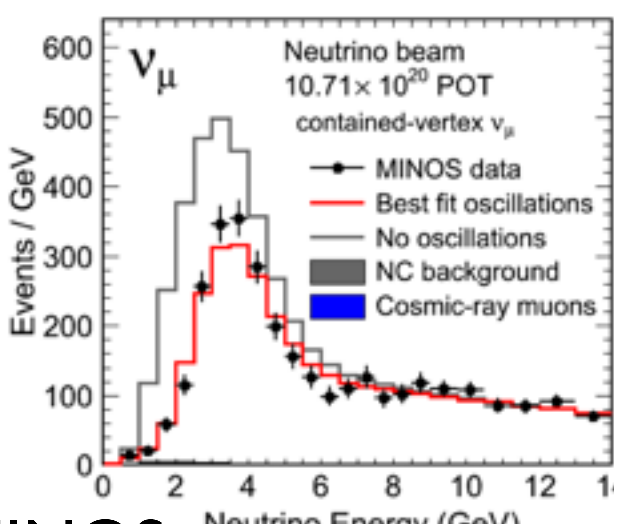
Received 12 July 1965

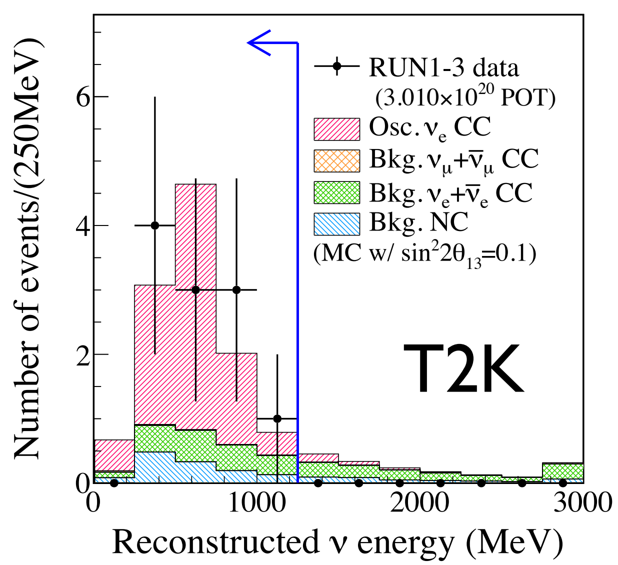


Super-Kamiokande, also MINOS



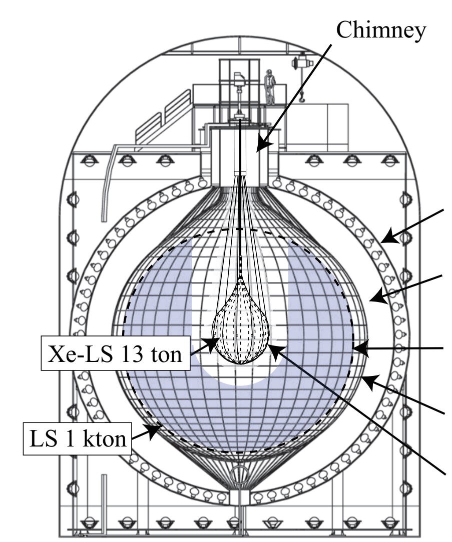
Accelerator neutrinos

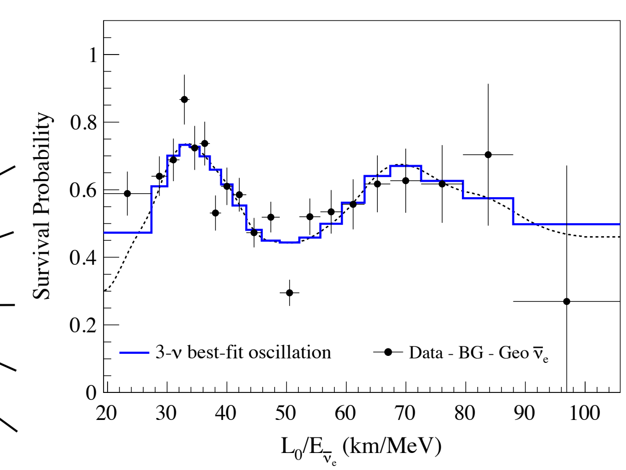




MINOS http://www-numi.fnal.gov

Reactor neutrinos: LBL

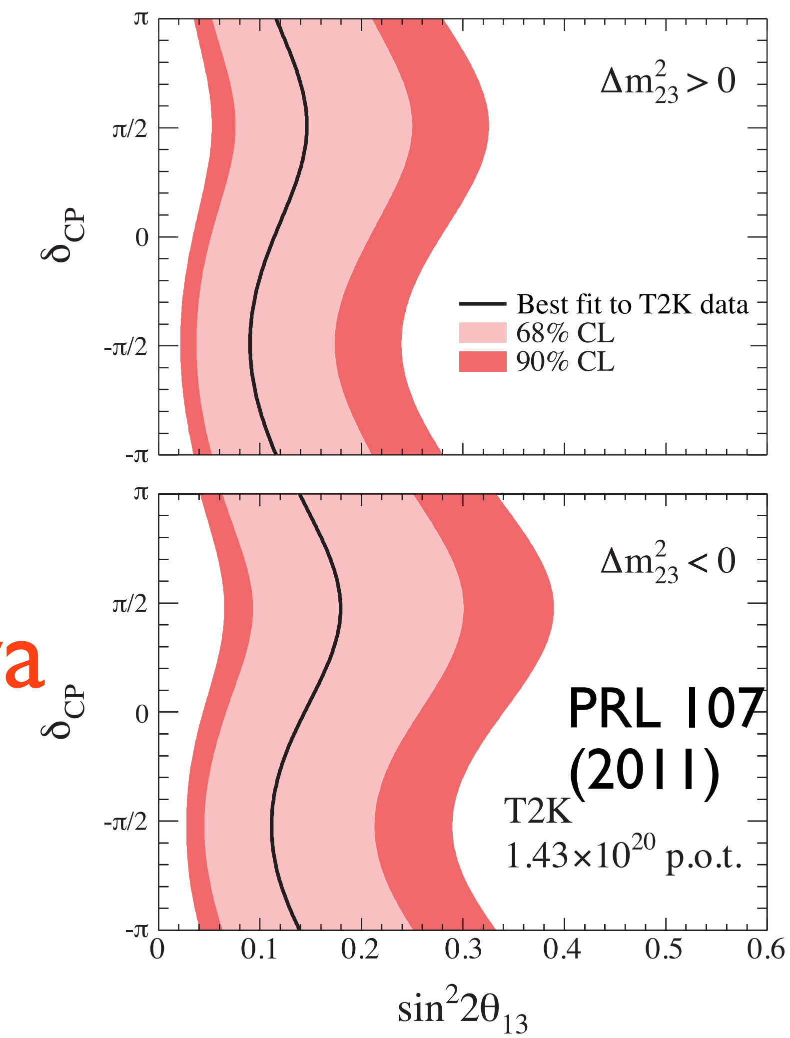




KamLAND, 1303.4667

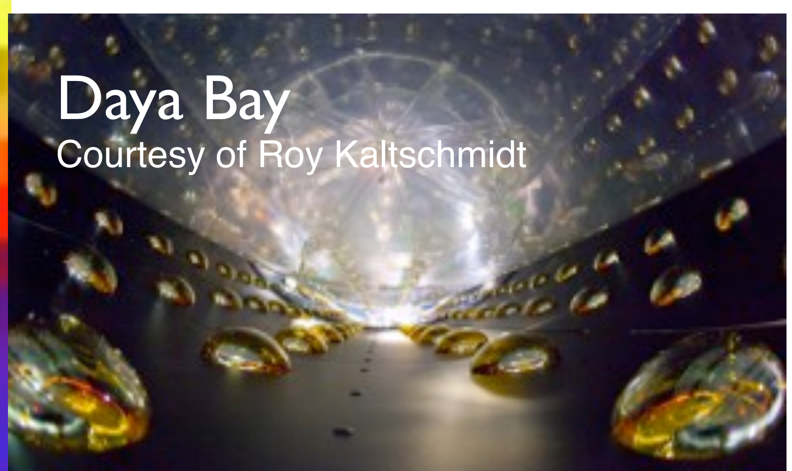
Theta13: the latest discovery

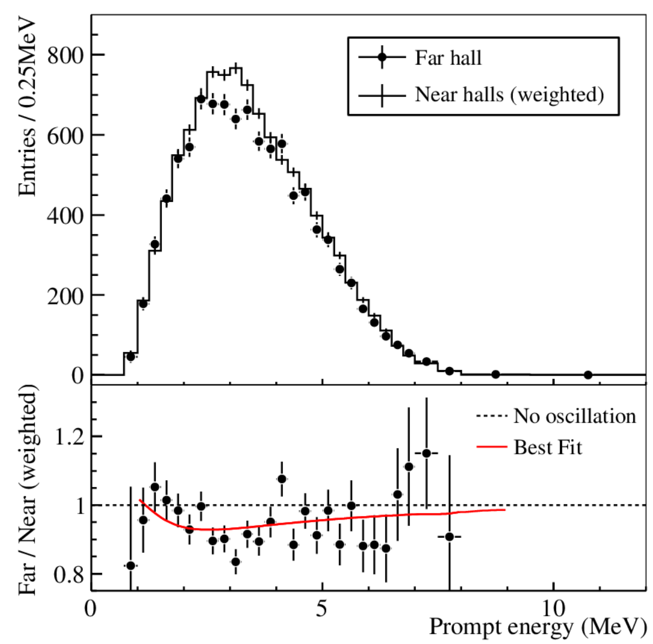
First hints of nonzero theta13 by T2K, MINOS and DoubleCHOOZ in 2011.



PRL 107 (2011)

In 2012, these hints were confirmed by Daya Bay and RENO.





Daya Bay, PRL 108 (2012)

Observed: 9901 neutrinos at far site,
Prediction: 10530 neutrinos if no oscillation

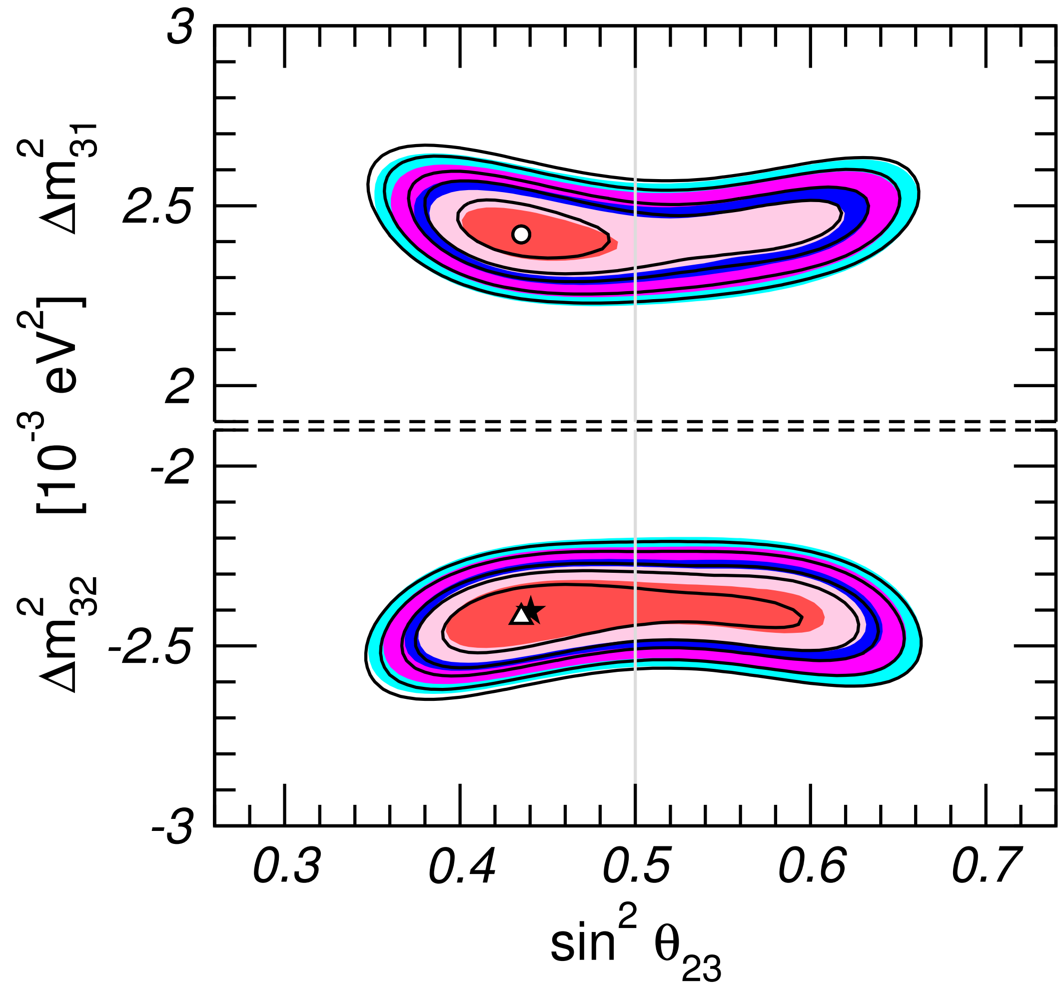
R = 0.940 ±0.011 (stat) ±0.004 (syst)

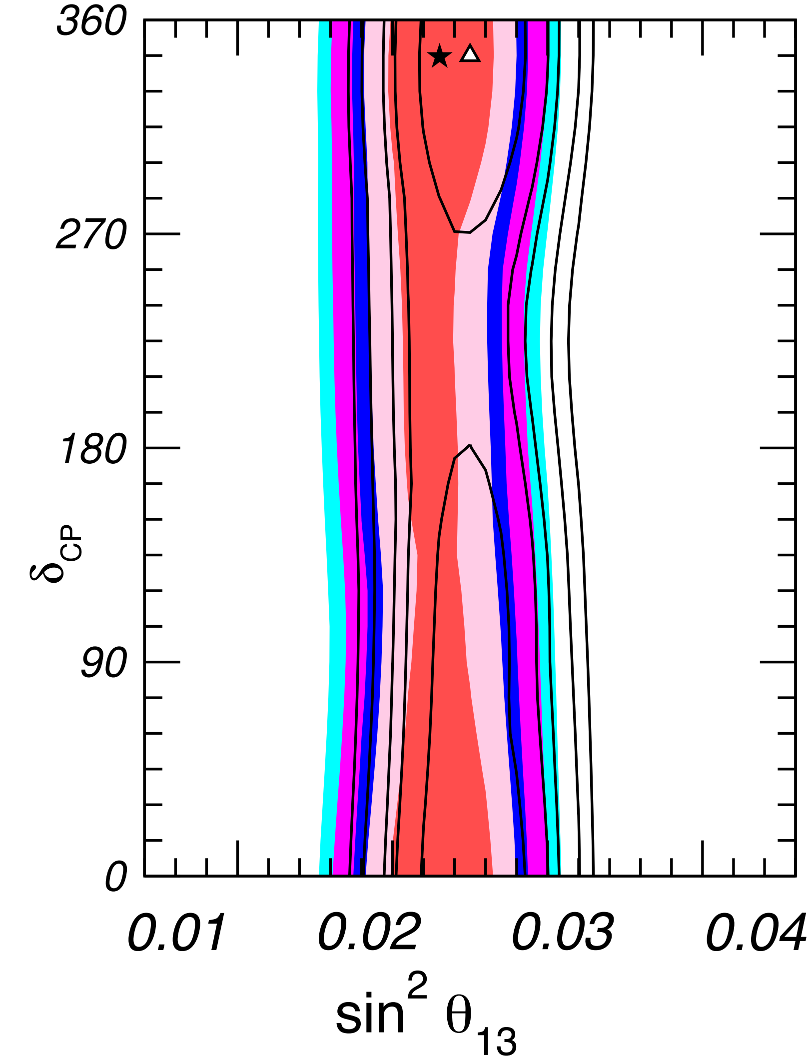
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$$

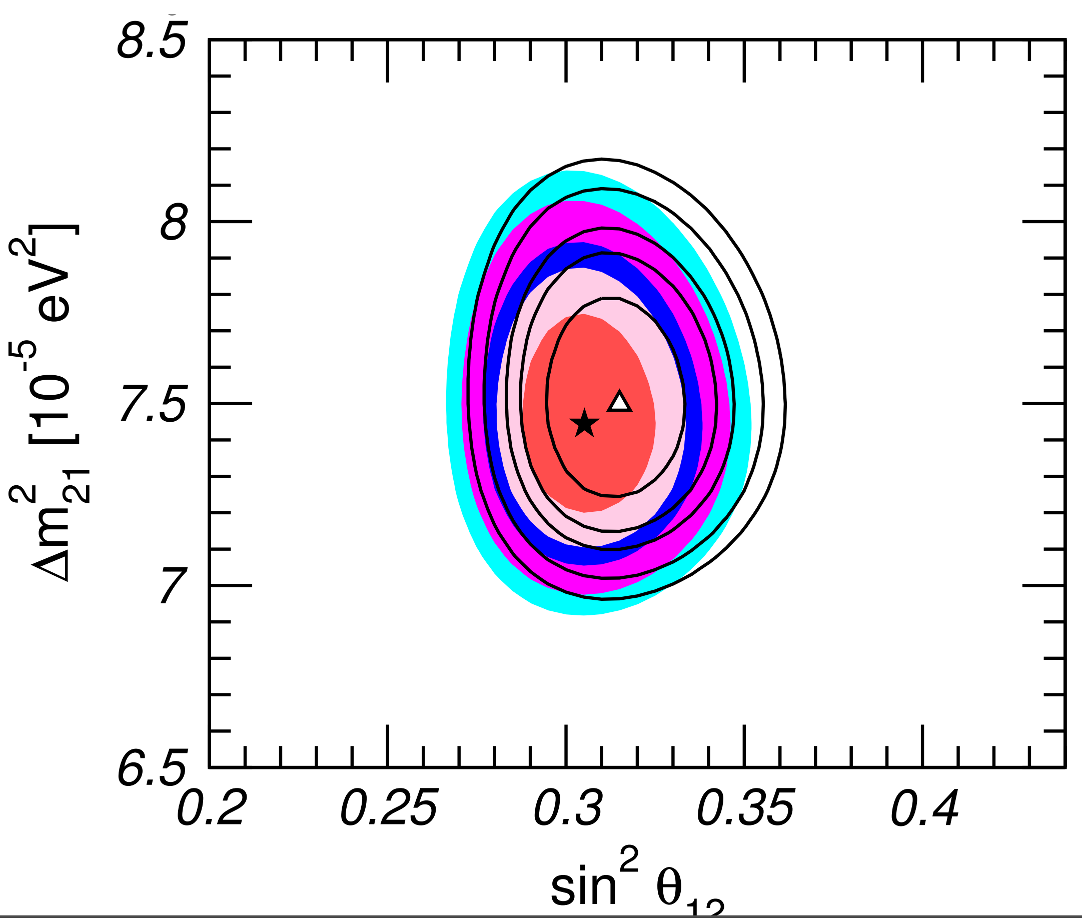
Y. Wang, March 2012

See Y. Wang's talk

This discovery has very important implications for the future neutrino programme and understanding of origin of mixing.







NuFit: M. C. Gonzalez-Garcia et al., 1209.3023

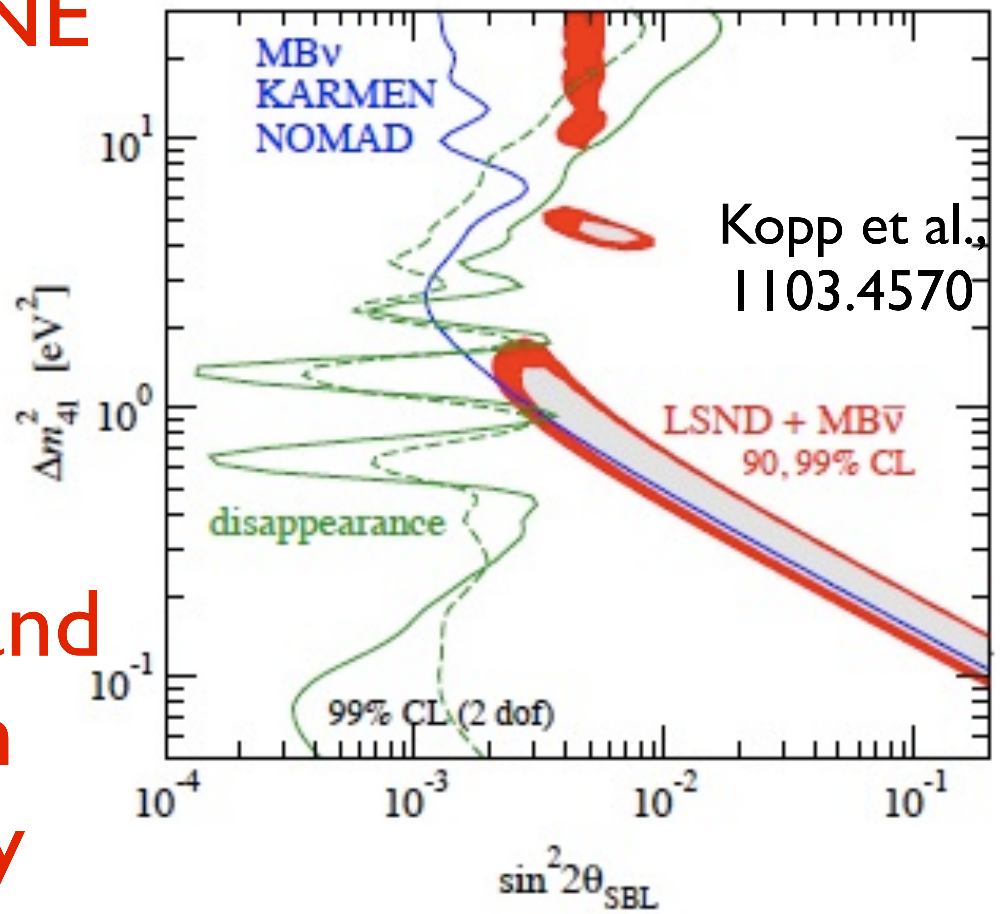
νfit Global fit to neutrino oscillation data

www.invisibles.eu

All oscillation parameters are measured with good precision, except for the mass hierarchy and the delta phase. One needs to check the 3-neutrino paradigm (sterile neutrino?).

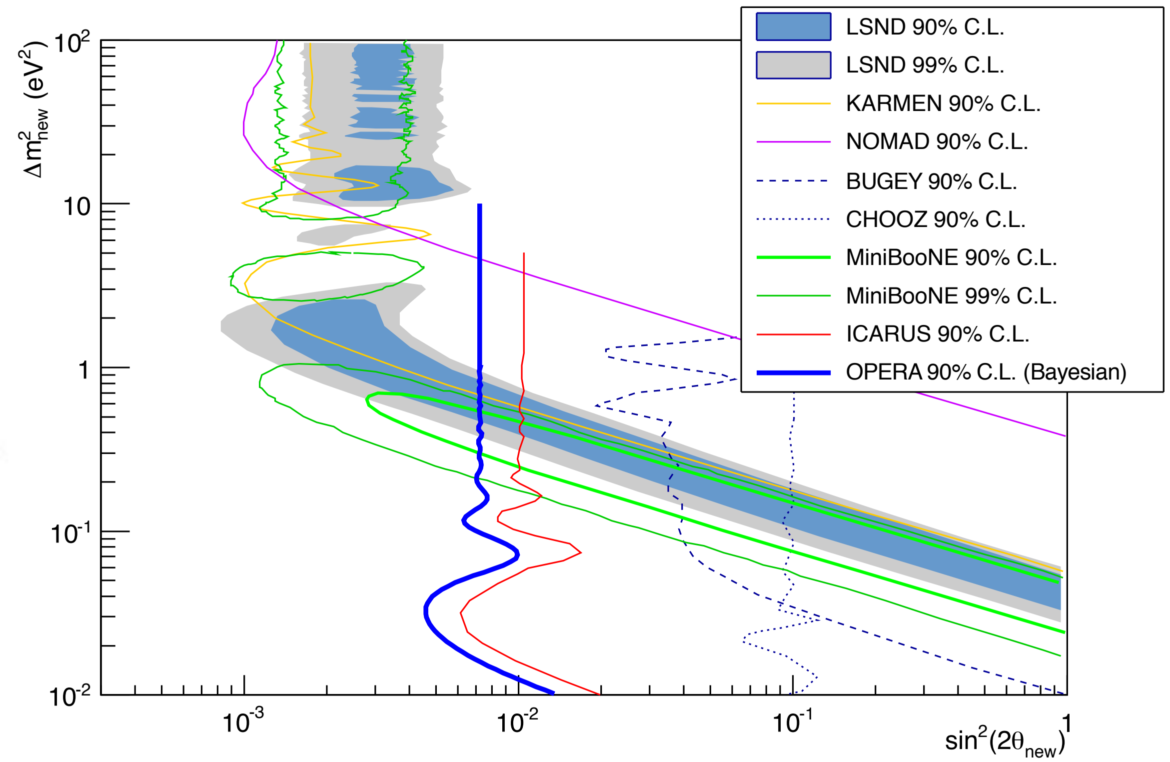
Anomalies

SBL: LSND and MiniBooNE



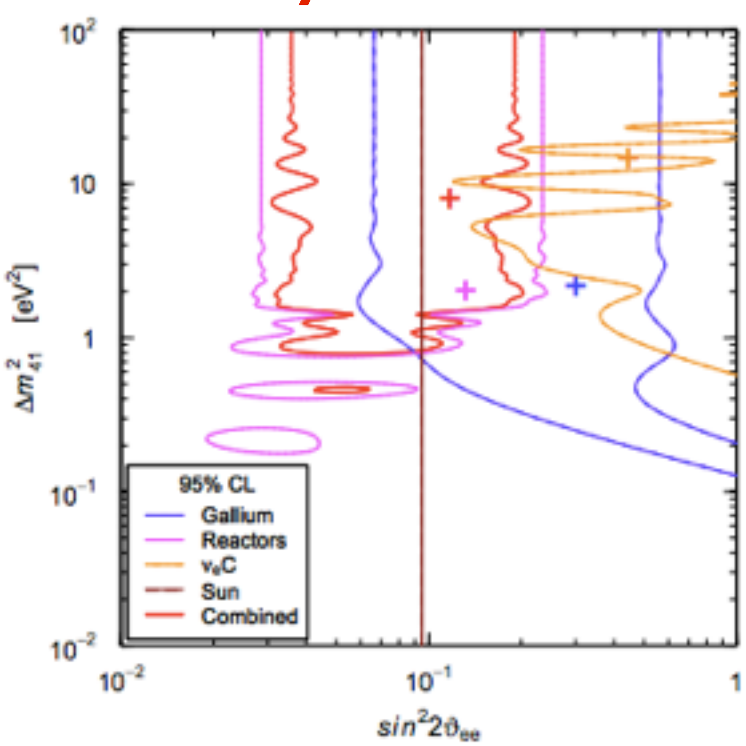
Kopp et al., 1103.4570

ICARUS and OPERA new bounds



OPERA, 1303.3953

Reactor and Gallium anomaly

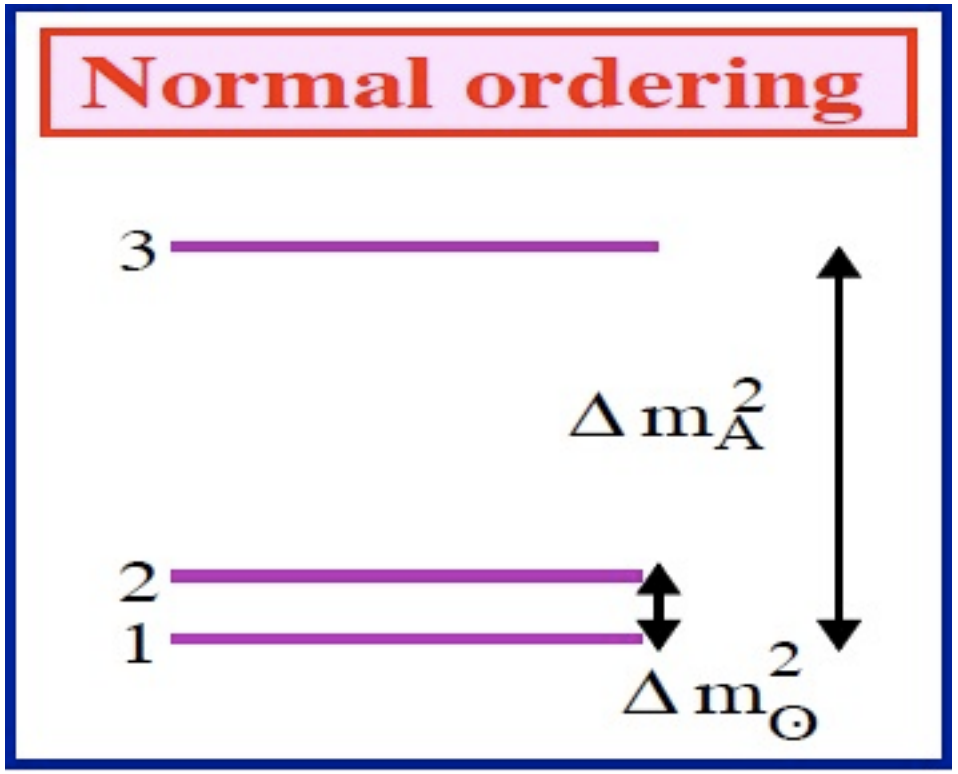


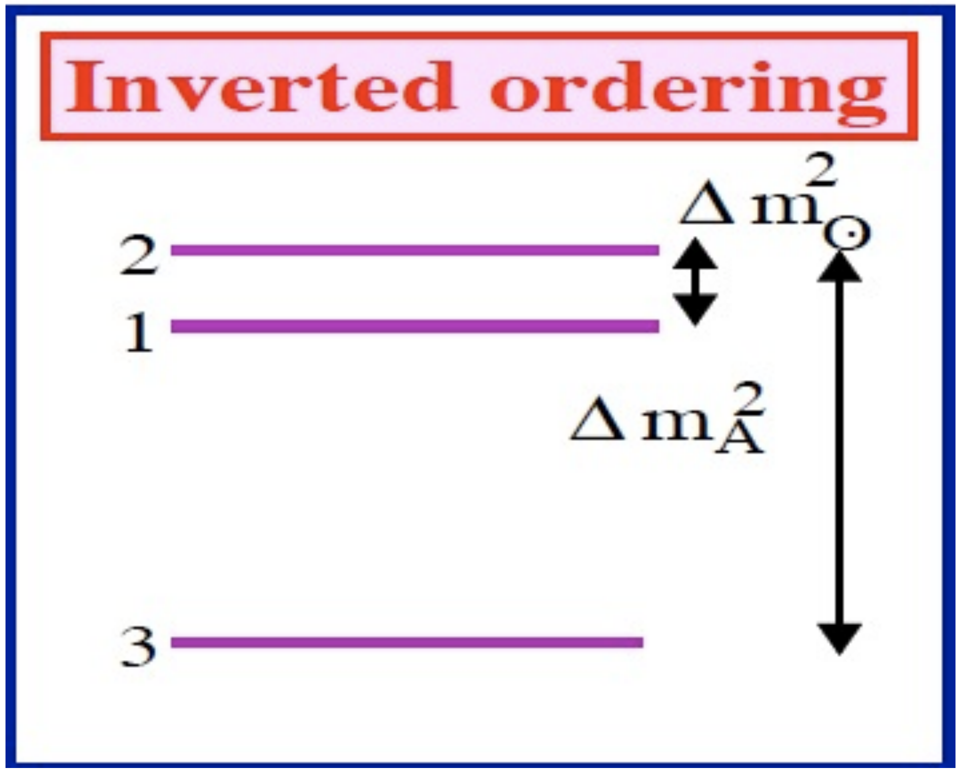
Various hints of oscillations with $\Delta m^2 \sim 1\,\mathrm{eV}^2$ but there is tension between appearance and disappearance experiments.

Giunti et al., 1210.5715, See also Mention et al., Huber et al., Zhang et al.

Present status of neutrino physics

$\Delta m^2_{\rm s} \ll \Delta m^2_{\rm A}$ implies at least 3 massive neutrinos.





$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm sol}}$$
$$m_3 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A}}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A} - \Delta m^2_{\rm sol}}$$
$$m_2 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A}}$$

Measuring the masses requires: $m_{\rm min}$ and the ordering.

Masses are much smaller than the other fermions.

Neutrino mixing

Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix, which enters in the CC interactions

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

Flavour states — Mass states

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\sum_{k\alpha}\left(U^*_{\alpha k}\bar{\nu}_{kL}\gamma^\rho l_{\alpha L}W_\rho + \text{h.c.}\right)$$

Large angles

CPV?

$$U = \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor } \theta_\odot \sim 30^o} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atm, Acc. } \theta_A \sim 45^o}$$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}}_{\text{CPV phase}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor, Acc. } \theta_{13} \sim 9^o} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}}_{\text{CPV Majorana phases}}$$

Mixing angles are much larger than in the quark sector.

Phenomenology questions for the future

- **1. What is the nature of neutrinos?**
- **2. What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **3. Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **4. What are the precise values of mixing angles?** Do they suggest a underlying pattern?
- **5. Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

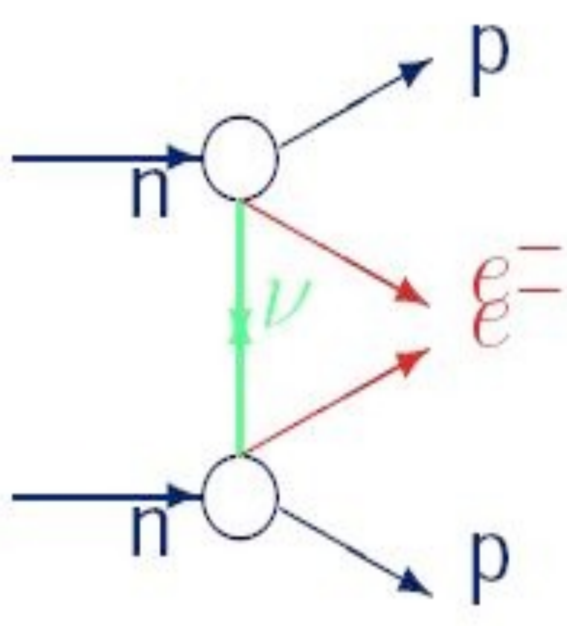
Question 1. Nature of Neutrinos

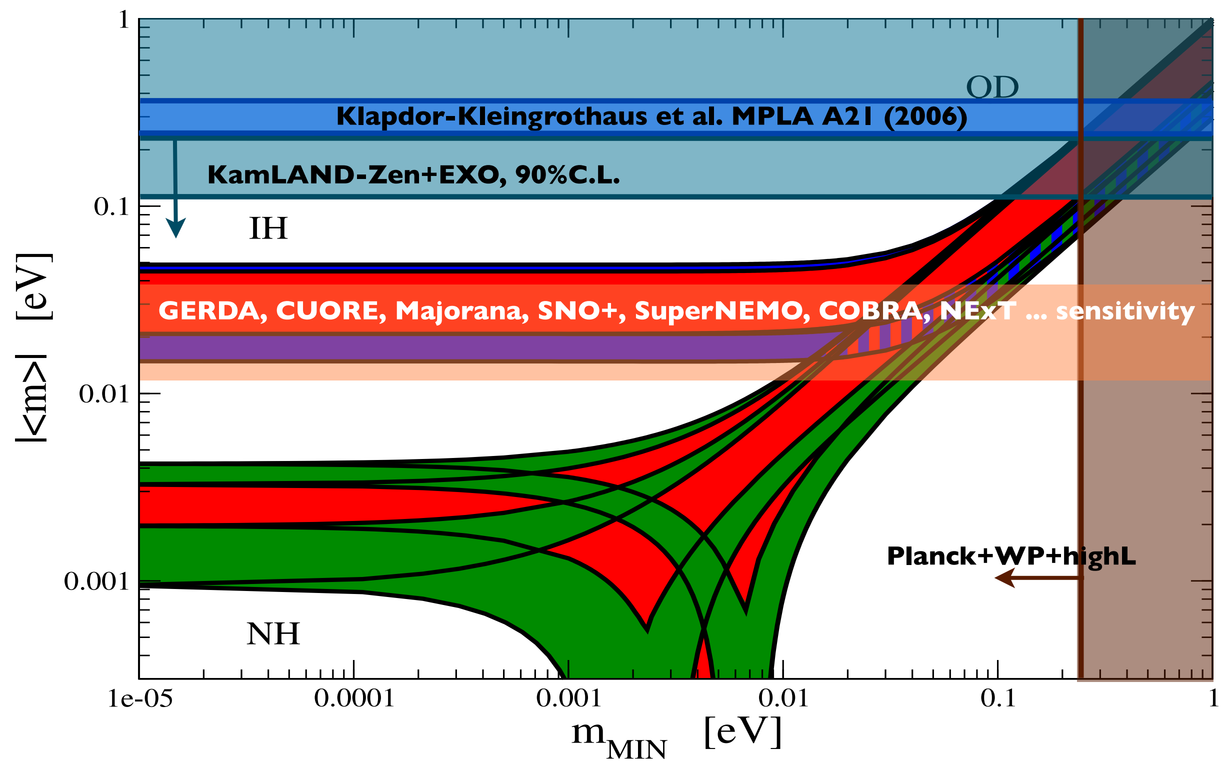
Neutrinos can be **Majorana** or **Dirac** particles. In the SM only neutrinos can be Majorana because they are neutral.

Majorana particles are indistinguishable from antiparticles.

Dirac neutrinos are labelled by the lepton number.

Testable in neutrinoless double beta decay





The **nature** of neutrinos is linked to the conservation of **Lepton number**. This information is crucial in understanding the Physics BSM and it can be linked to the existence of matter in the Universe.

Question 2. Neutrino masses

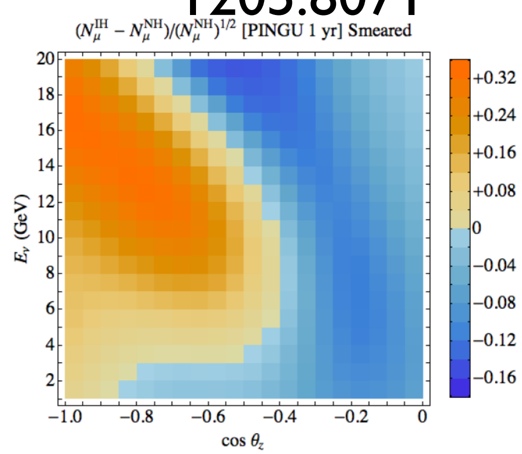
See S. Zeller's and M. Shiozawa's talks

- **Neutrino mass ordering (hierarchy)**
  - use matter effects in neutrino oscillations

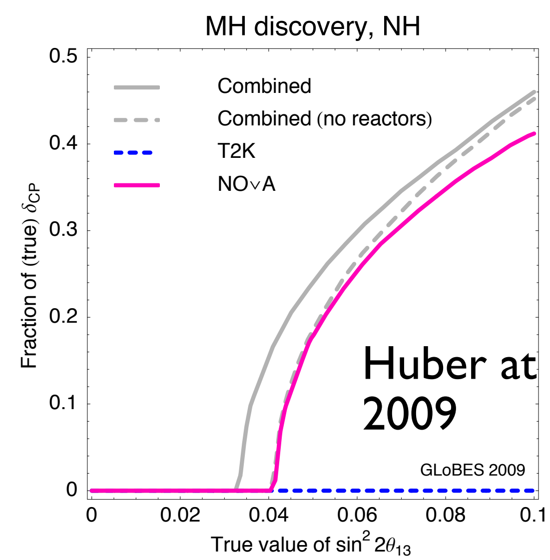
Future long baseline experiments: LBNE, LBNO, T2HK, nuFact

Atmospheric nus: ORCA, PINGU, INO

Akhmedov, Razzaque, Smirnov, 1205.8071



T2K and NOvA

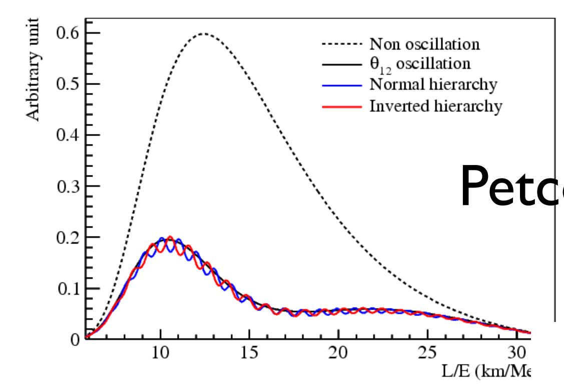


Huber at al., 2009

Thanks to A. Rubbia; LAGUNA-LBNO

K. Sakashita

- vacuum oscillations in reactors
- neutrinoless double beta decay

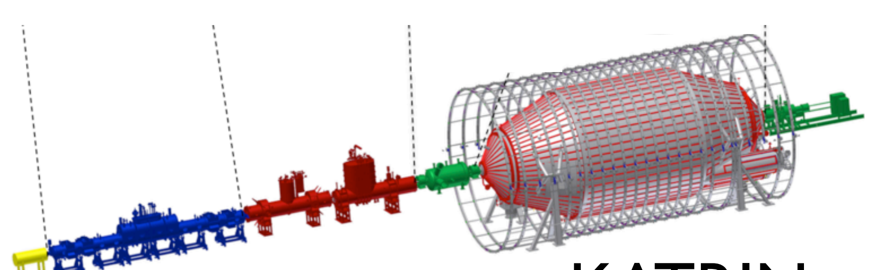


Petcov et al., 2001

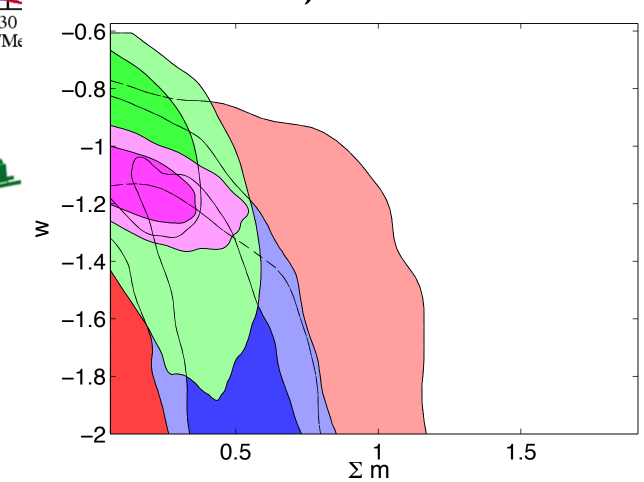
Giusarma et al., 1306.5544

- **Absolute mass scale**
  - KATRIN
  - cosmology
  - neutrinoless double beta decay

See C. Hall's talk



KATRIN



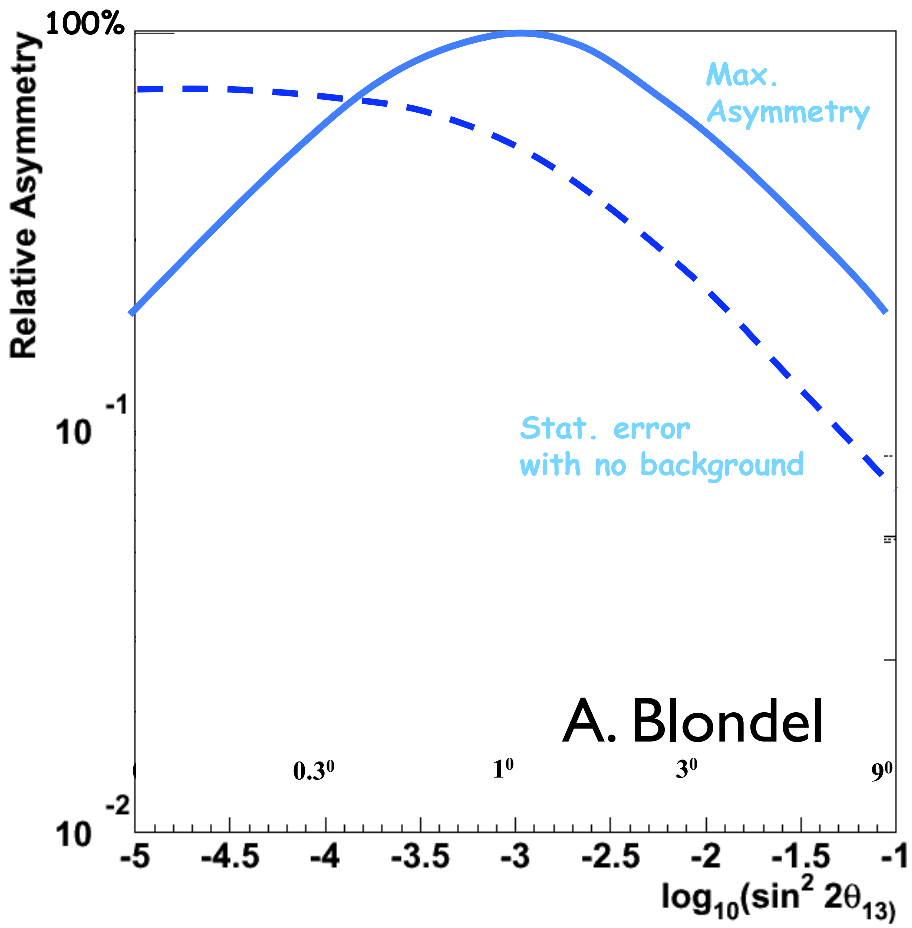
Question 3. CP-violation

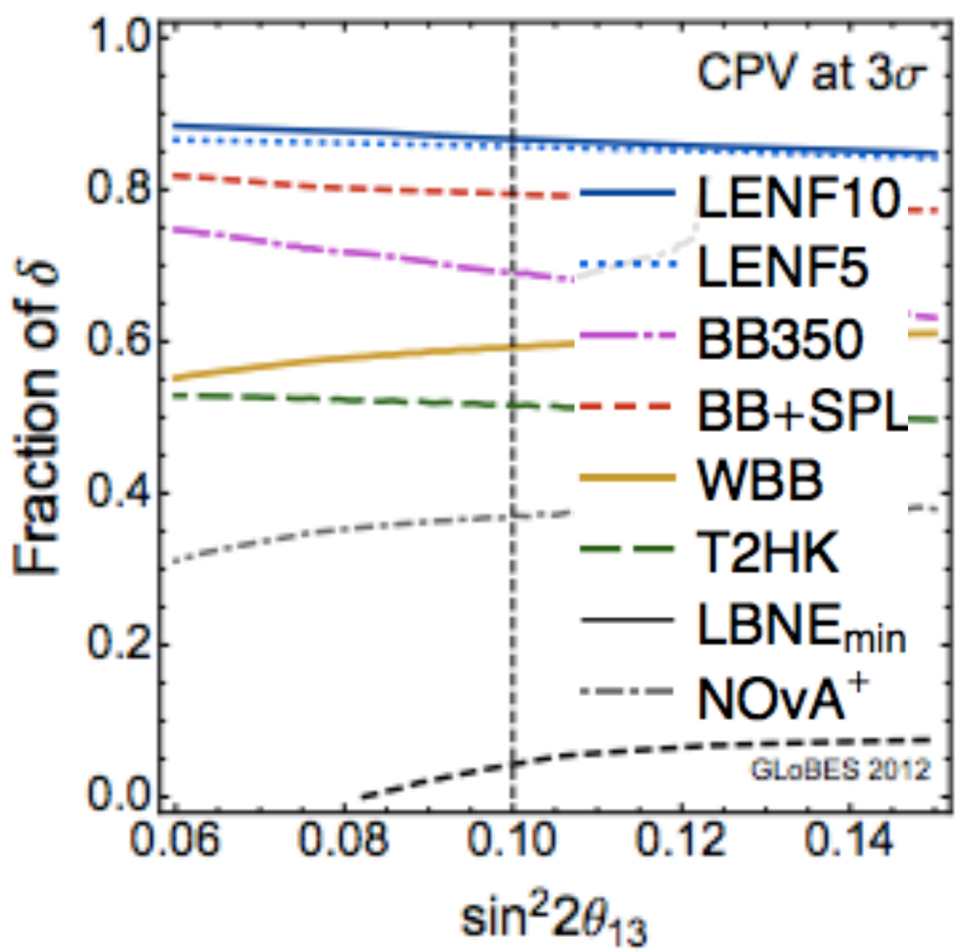
See S. Zeller's and M. Shiozawa's talks

CP-violation will manifest itself in neutrino oscillations, due to the delta phase. The CP-asymmetry:

$$P(\nu_\mu \to \nu_e; t) - P(\bar{\nu}_\mu \to \bar{\nu}_e; t) =$$
$$= 4 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \left[\sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{23}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \right]$$

CP-violation requires all angles to be nonzero.

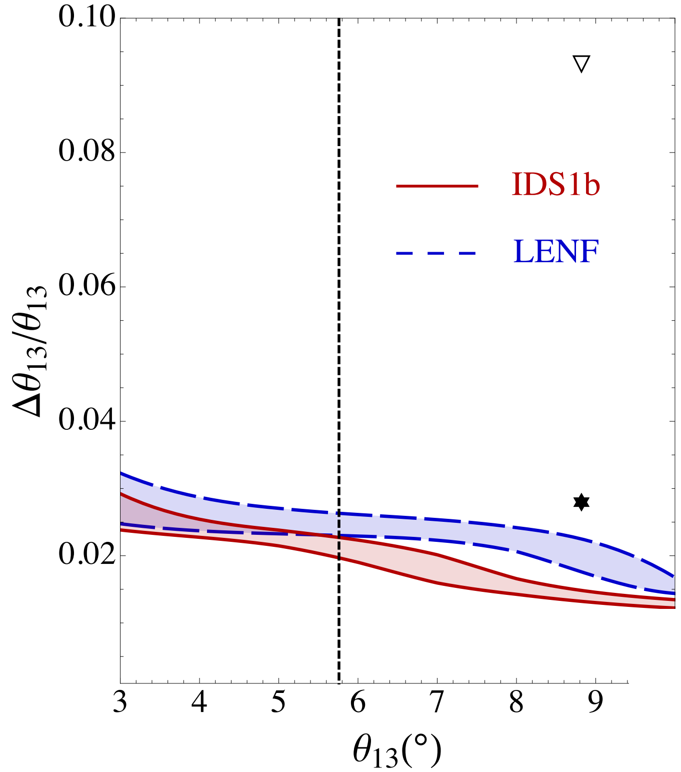




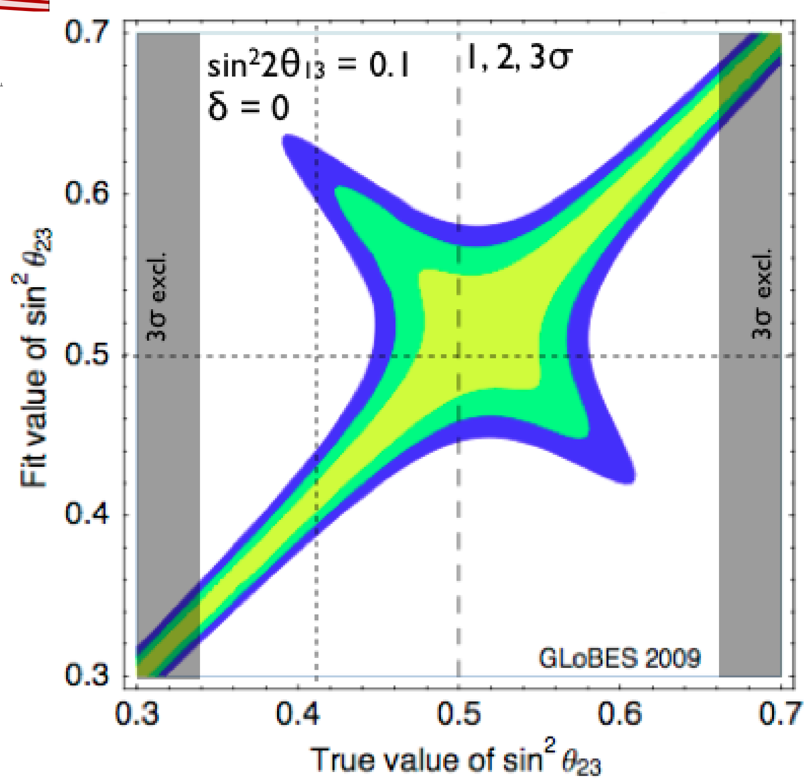
Coloma, Huber, Kopp, Winter, 1209.5973

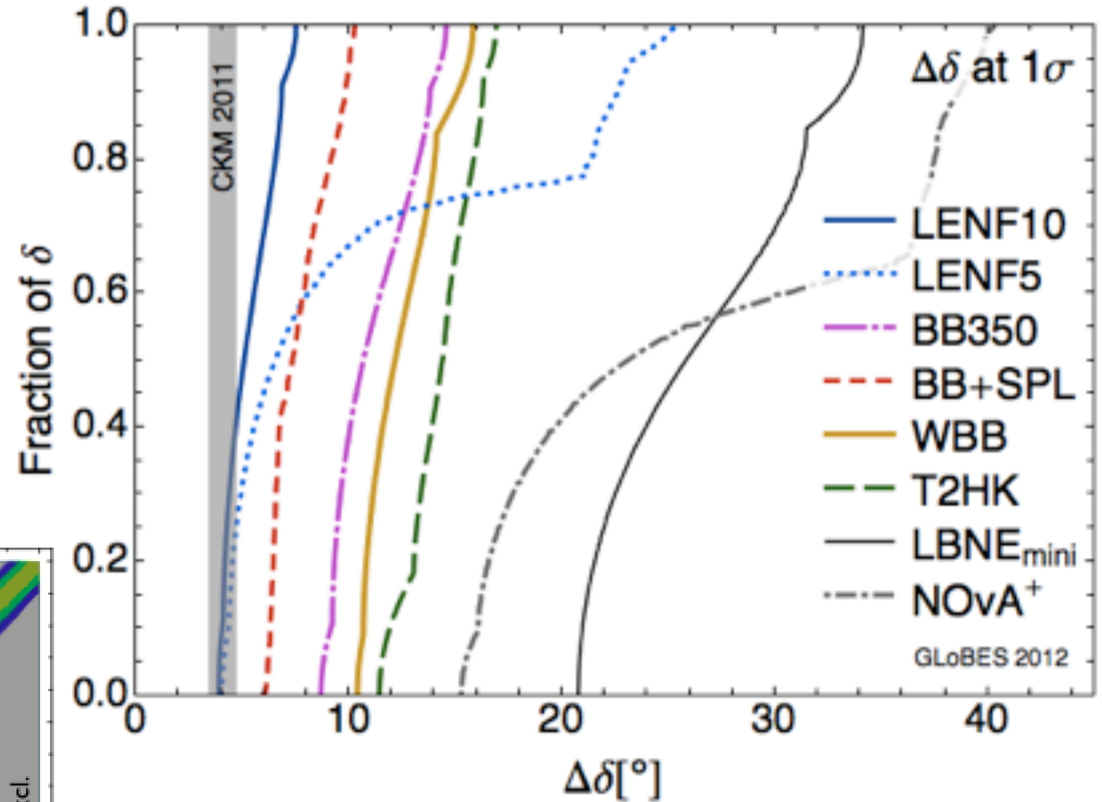
Question 4. Precision measurements

The precision measurement of the oscillation parameters will become very important once the mass hierarchy and CPV are established. LBL experiments can give information on $\theta_{23}, \ \theta_{13}, \ \delta$.



Coloma, Donini, Fernandez Martinez, Hernandez, 1203.5651





Coloma, Huber, Kopp, Winter, 1209.5973

Schwetz et al., 2009

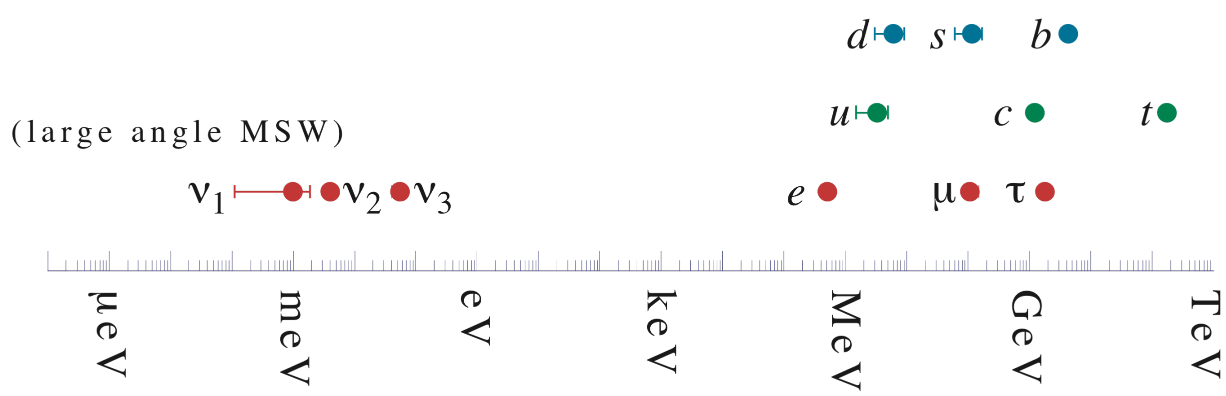
See S. Zeller's and M. Shiozawa's talks

The ultimate goal is to understand
- where do neutrino masses come from?
- why there is leptonic mixing? and what is at the origin of the observed structure?

Open window on Physics beyond the SM

Neutrino physics gives a new perspective on physics BSM.

1. Origin of masses



Why do neutrinos have mass? and why are they so much lighter?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

This information is **complementary** with the one which comes from flavour physics experiments and from colliders.

Neutrino Masses in the SM and beyond

In the SM, neutrinos do not acquire mass and mixing:

- like the other fermions as there are no right-handed neutrinos.

$$m_e \bar{e}_L e_R \qquad\qquad m_\nu \bar{\nu}_L \nu_R$$

Solution: Introduce ν_R for Dirac masses

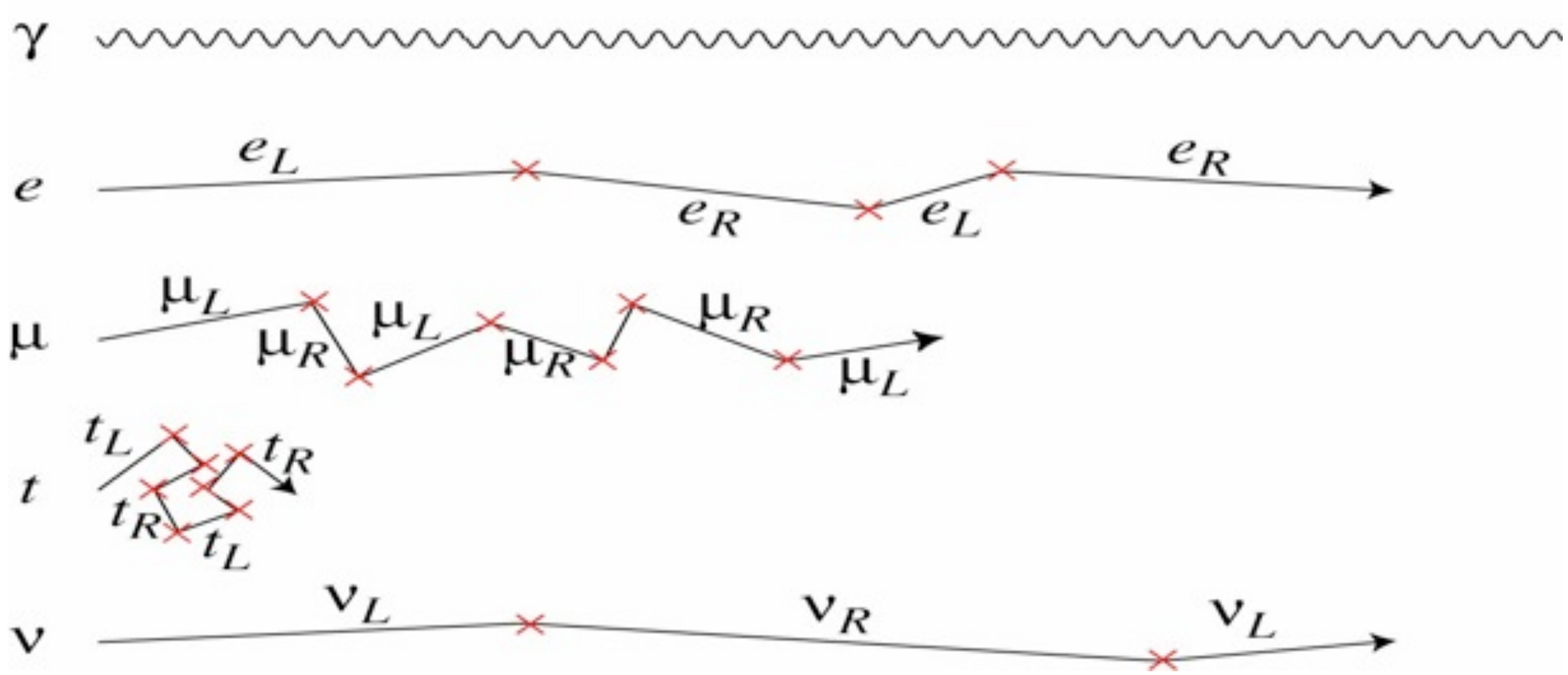
- they do not have a Majorana mass term

$$M \nu_L^T C \nu_L$$

as this term breaks the SU(2) gauge symmetry.
Solution: Introduce an SU(2) scalar triplet or gauge invariant non-renormalisable terms (D>4). This term breaks Lepton Number.

Dirac Masses

Neutrino masses in the sub-eV range require very small couplings to the Higgs boson.



Thanks to
H. Murayama

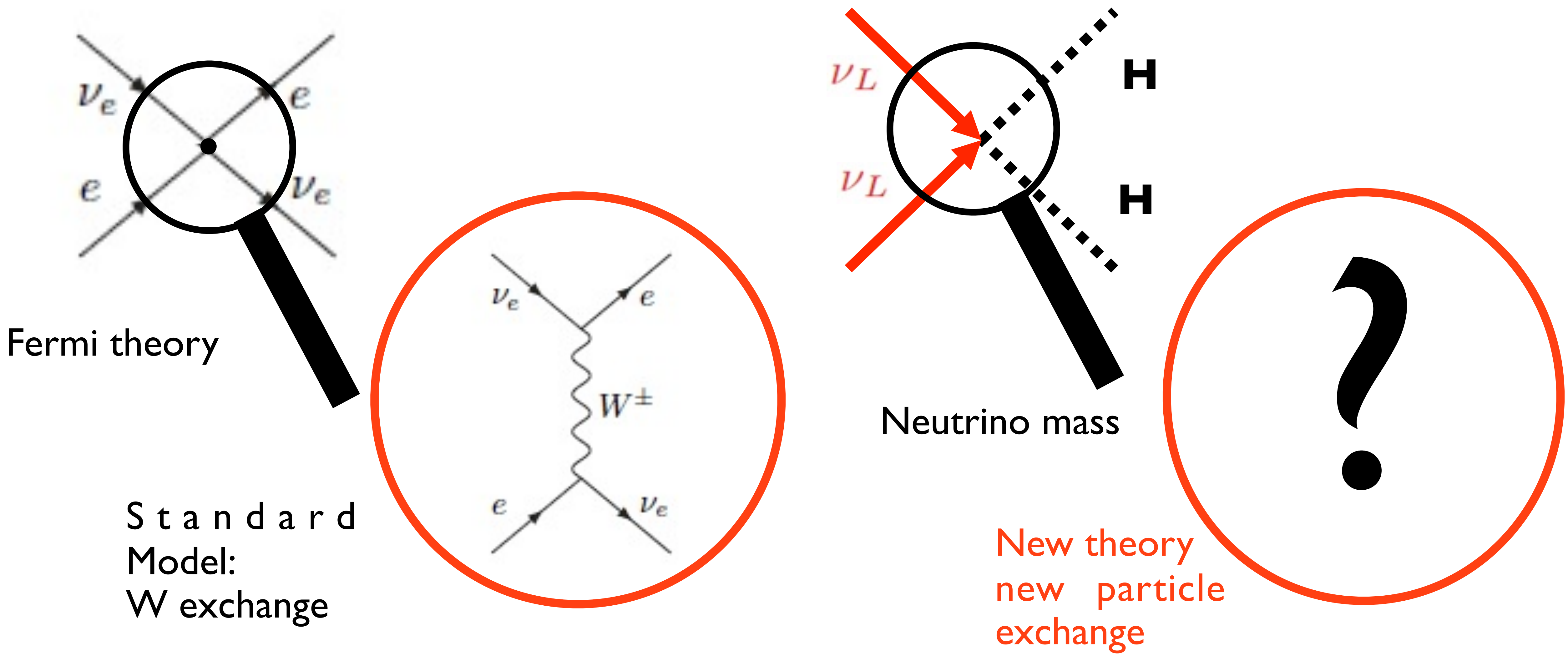
$$\mathcal{L} = y_\nu \bar{L} \cdot H \nu_R + \text{h.c.}$$

$$y_\nu = \frac{m_\nu}{v} = \frac{0.1\,\text{eV}}{250\,\text{GeV}} = 4 \times 10^{-13}$$

Many theorists consider this explanation of neutrino masses unnatural, unless an explanation can be given for the extreme smallness of the coupling (e.g. extra-D models).

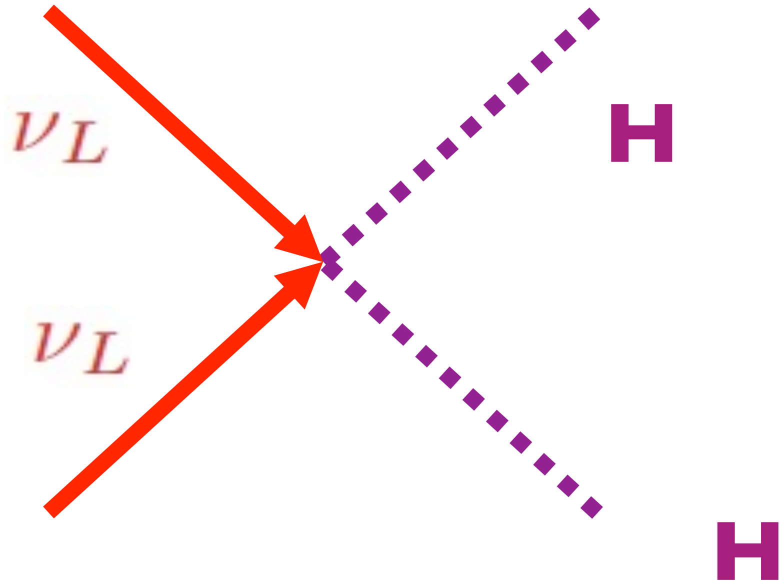
Majorana Masses

If neutrino are Majorana particles, a **Majorana mass** can be generated and can arise as the **low energy realisation of a higher energy theory (new mass scale!)**.



$$-\mathcal{L} = \lambda \frac{\nu_L H \, \nu_L H}{M} = \frac{\lambda v^2}{M} \nu_L^T C \nu_L$$

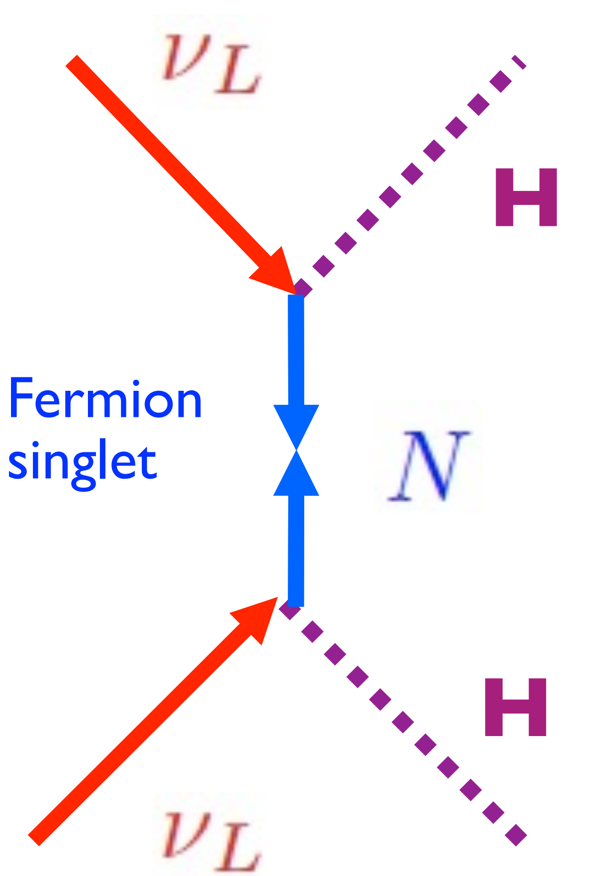
D=5 term



$$\frac{\nu_L H \; \nu_L H}{\Lambda}$$

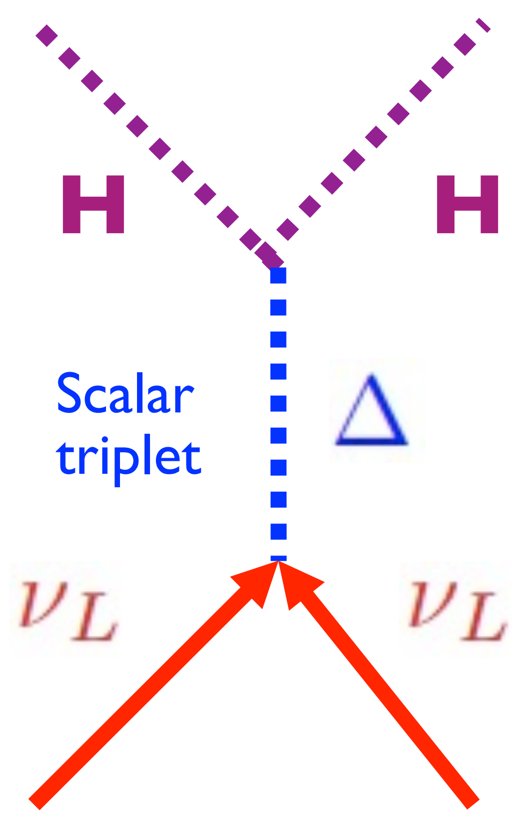
Lepton number violation!

See-saw Type I



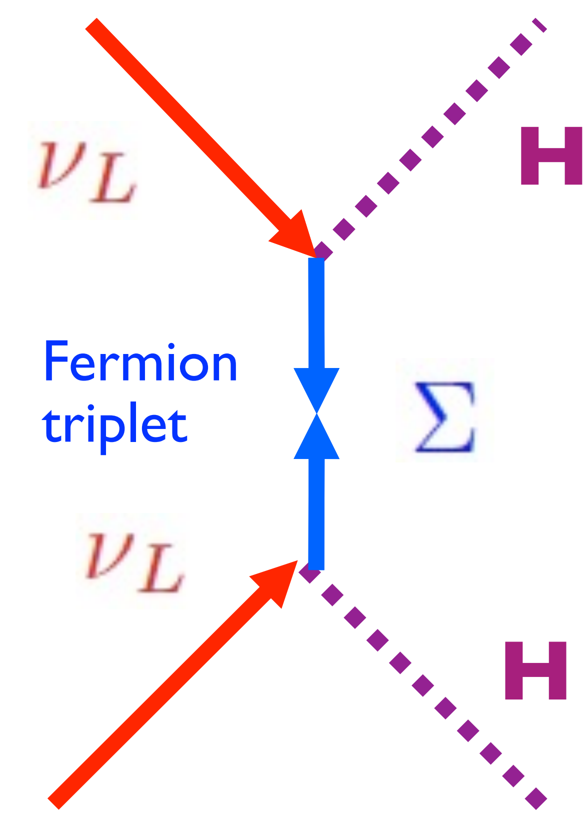
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II



Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

See-saw Type III



Ma, Roy, Senjanovic, Hambye

What is the new physics scale?

Thanks also to P. Hernandez

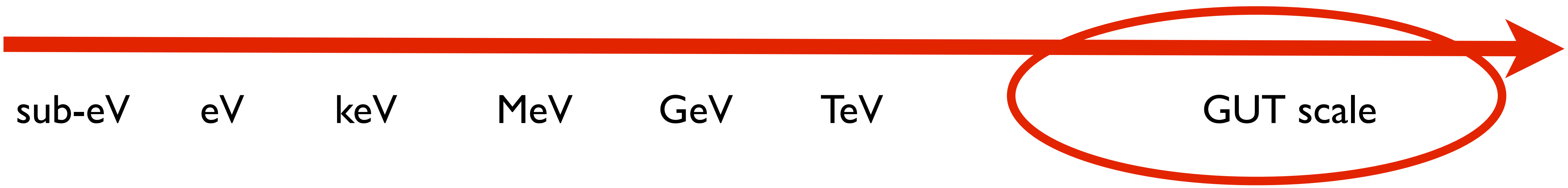
The **new Standard Model** will contain

- new particles at a new physics scale
- new interactions.

Coupling with the dark sector. neutrinos can be a portal to new physics:

$$\mathcal{L}_\nu = y\, \bar{L} \cdot H \text{ new}$$

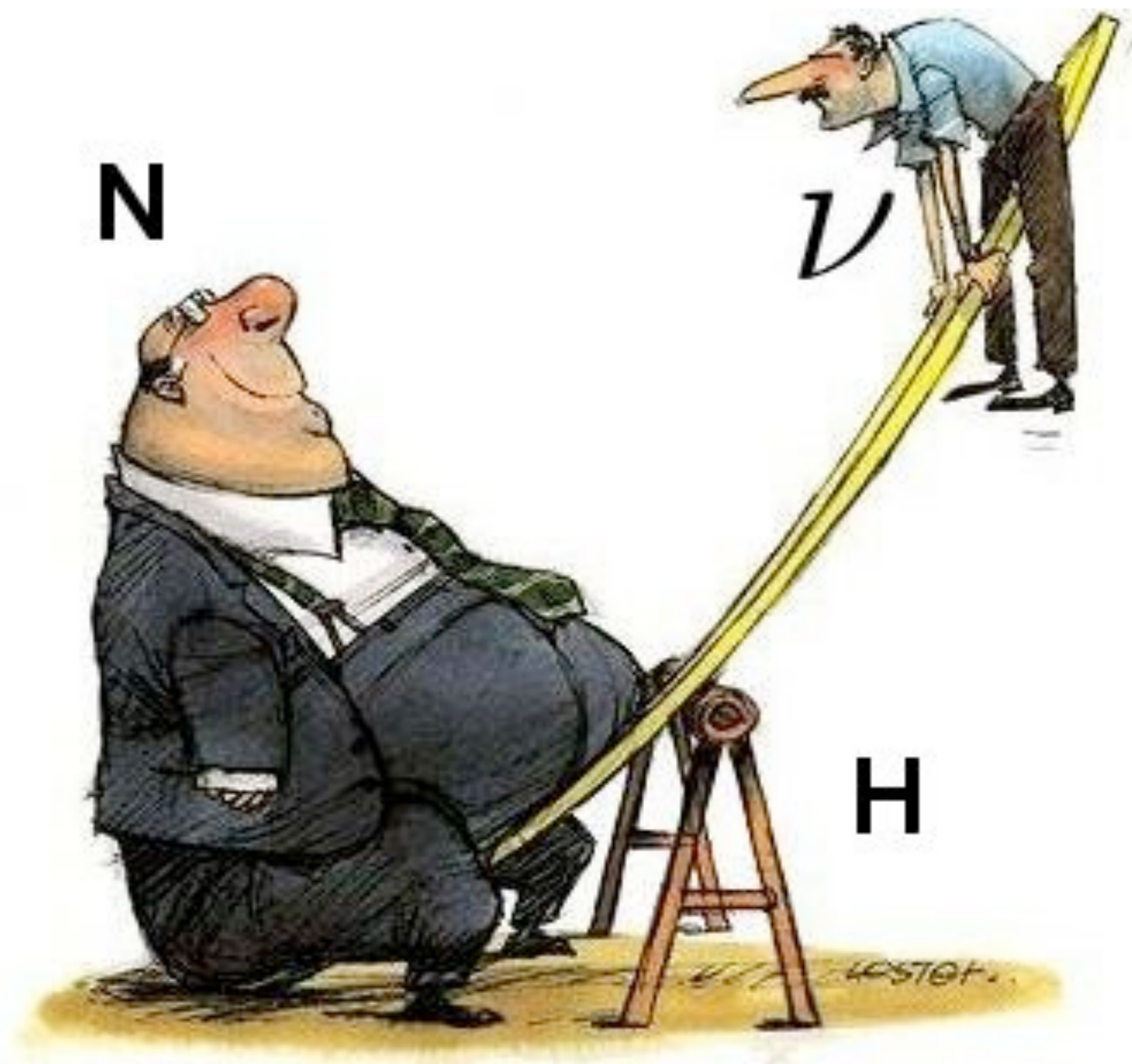
What is the new physics scale?



Signatures

- Neutrino masses
- Charged lepton flavour violation
- Indirect signals (proton decay)
- Leptogenesis

GUT scale: See-saw mechanism type I



- Introduce a right handed neutrino **N**
- Couple it to the Higgs and left handed neutrinos with Yukawa couplings similar to the other fermions

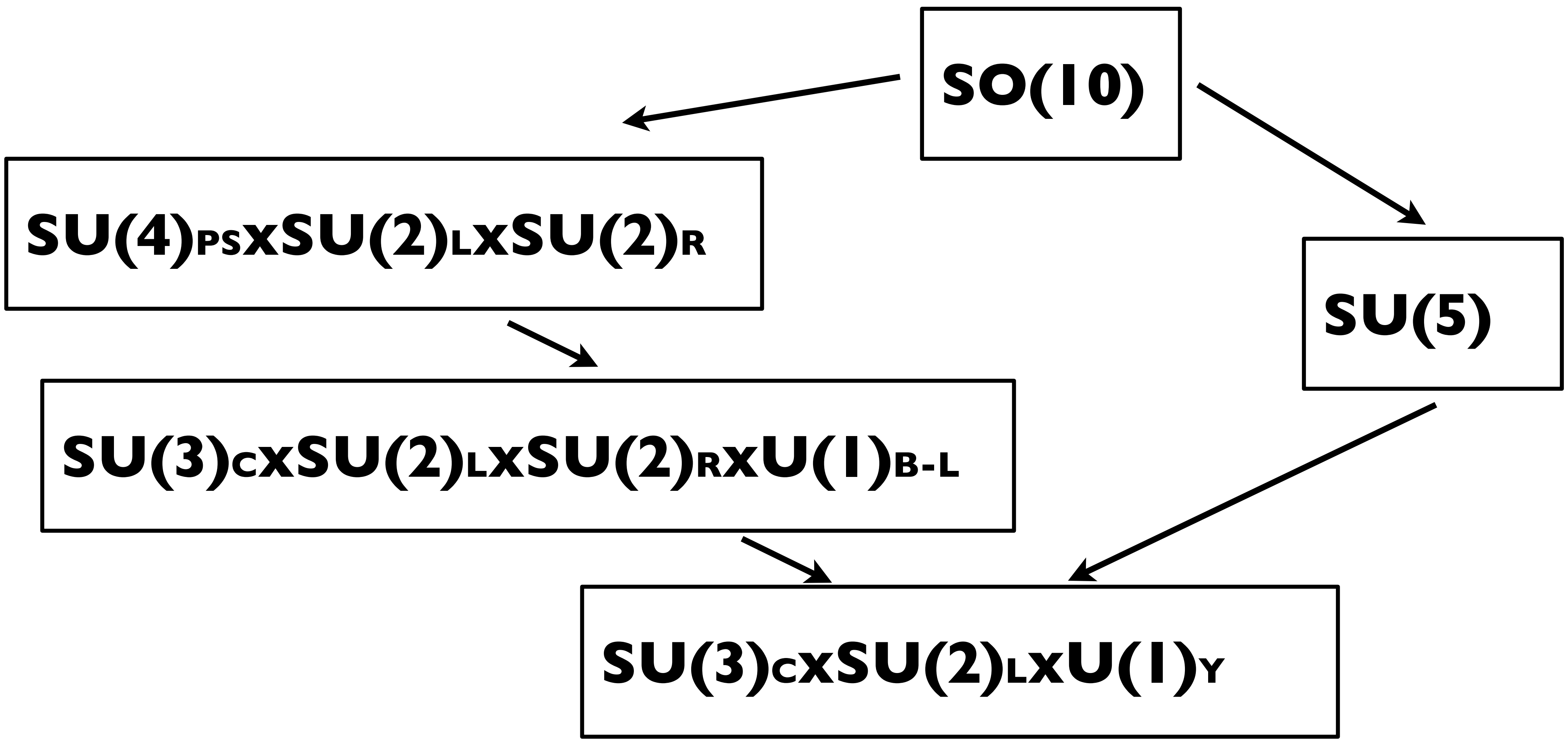
$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_\nu = \frac{y_\nu^2 v_H^2}{M_N}$$

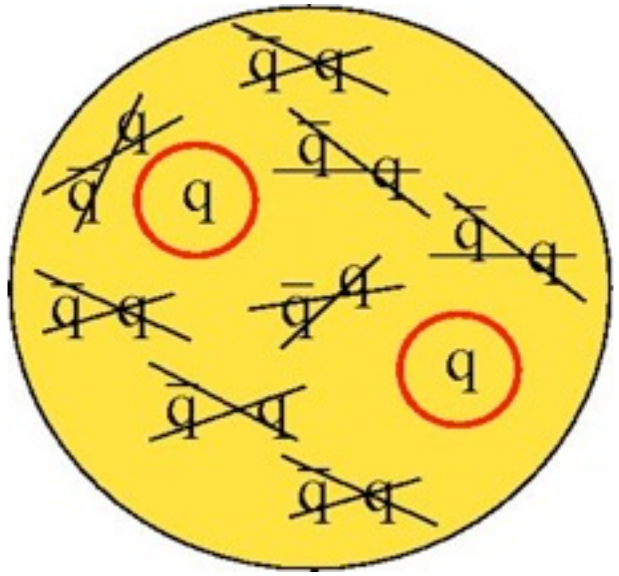
$$M_N \sim 10^{14}\ \mathrm{GeV}$$

The see-saw can emerge naturally in **GUTheories**: e.g. SO(10). They provide the necessary elements: N, large M and L violation.



They typically lead to relations between quark and lepton masses. Understanding the origin of neutrino masses might shed light on the physics at energy scales which could not be tested directly in any experiments.

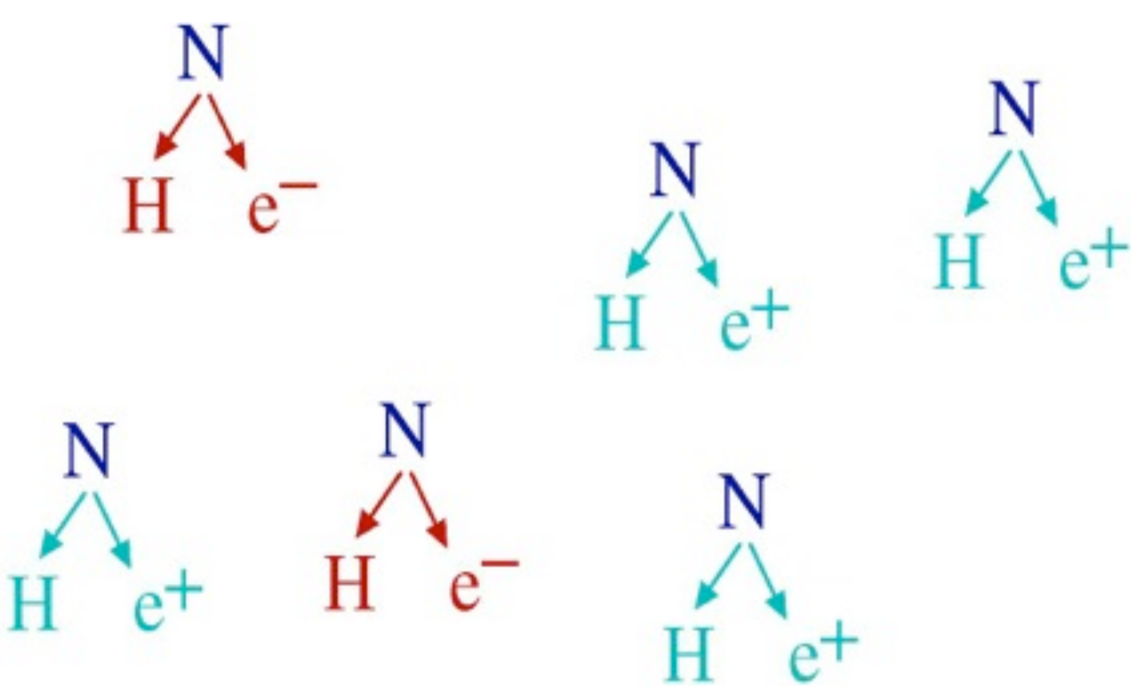
In the Early Universe



As the temperature drops, only quarks are left:

$$Y_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.2) \times 10^{-10}$$

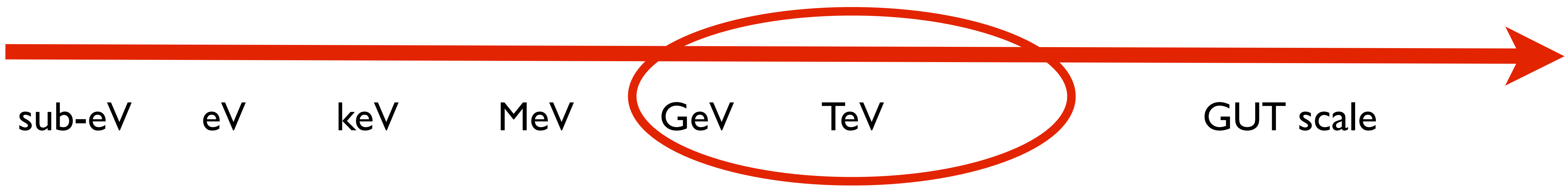
The excess of quarks can be explained by **Leptogenesis** (Fukugita, Yanagida): the heavy N responsible for neutrino masses generate a lepton asymmetry.



Excess of $e^+ \longrightarrow$ excess of q over $\bar{q}$

Observing L violation and CPV would constitute a **strong hint in favour of leptogenesis as the origin of the baryon asymmetry**.

What is the new physics scale?

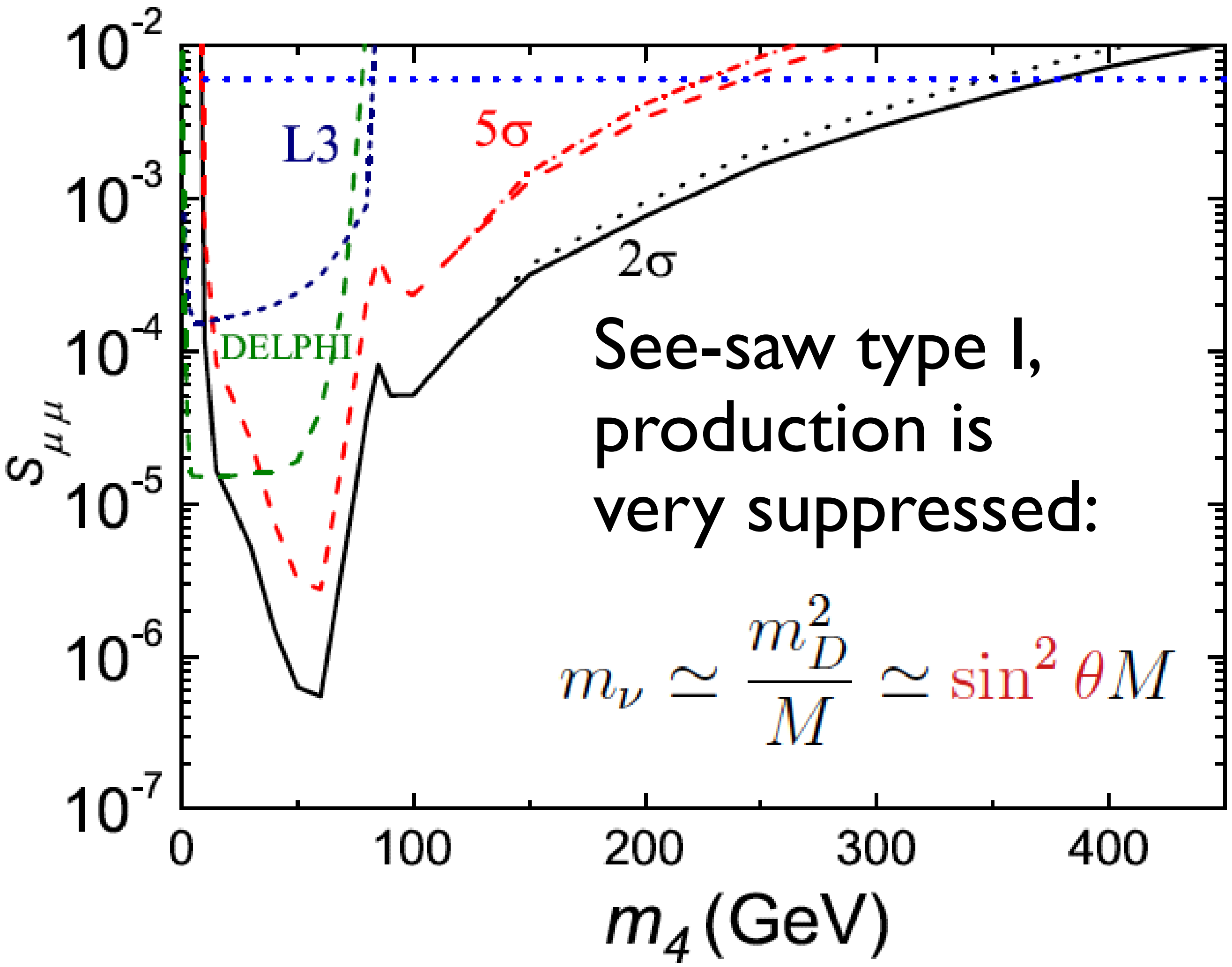


Signatures

- Neutrino masses
- Charged lepton flavour violation
- Direct signals in colliders
- (Leptogenesis)

TeV scale models

For smaller Yukawa couplings, small masses can arise from new physics at the TeV scale: in principle testable at the LHC by looking at same-sign dileptons.



See-saw type I, production is very suppressed:

$$m_\nu \simeq \frac{m_D^2}{M} \simeq \sin^2\theta M$$

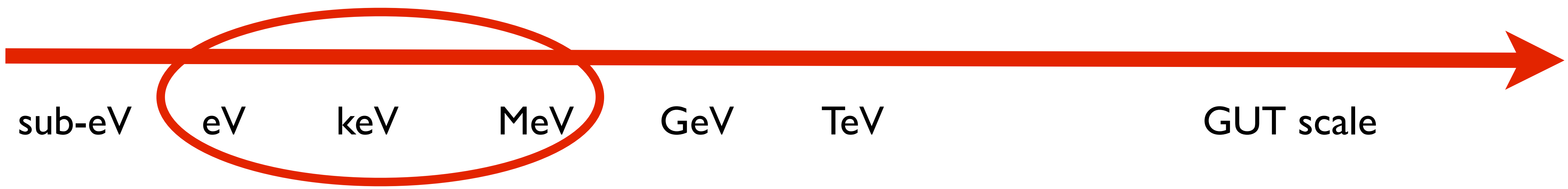
Atre et al., 0901.3589

- Gauge B-L: pp → Z' → N N
- See-saw type II: Scalar Triplets
- Triplet see-saw. Triplet N produced in gauge interactions

$$pp \to N^+ N^0 \to \ell_1^+ \ell_2^+ Z W^-$$

- Left-Right models via W_R
- Inverse or extended see-saw models
- R-parity violating SUSY

What is the new physics scale?

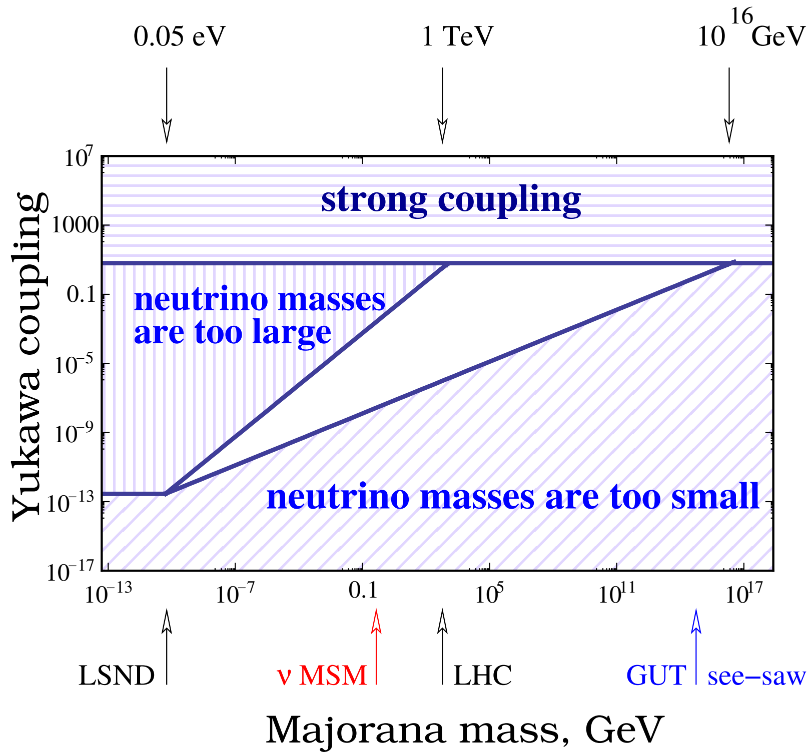


Signatures

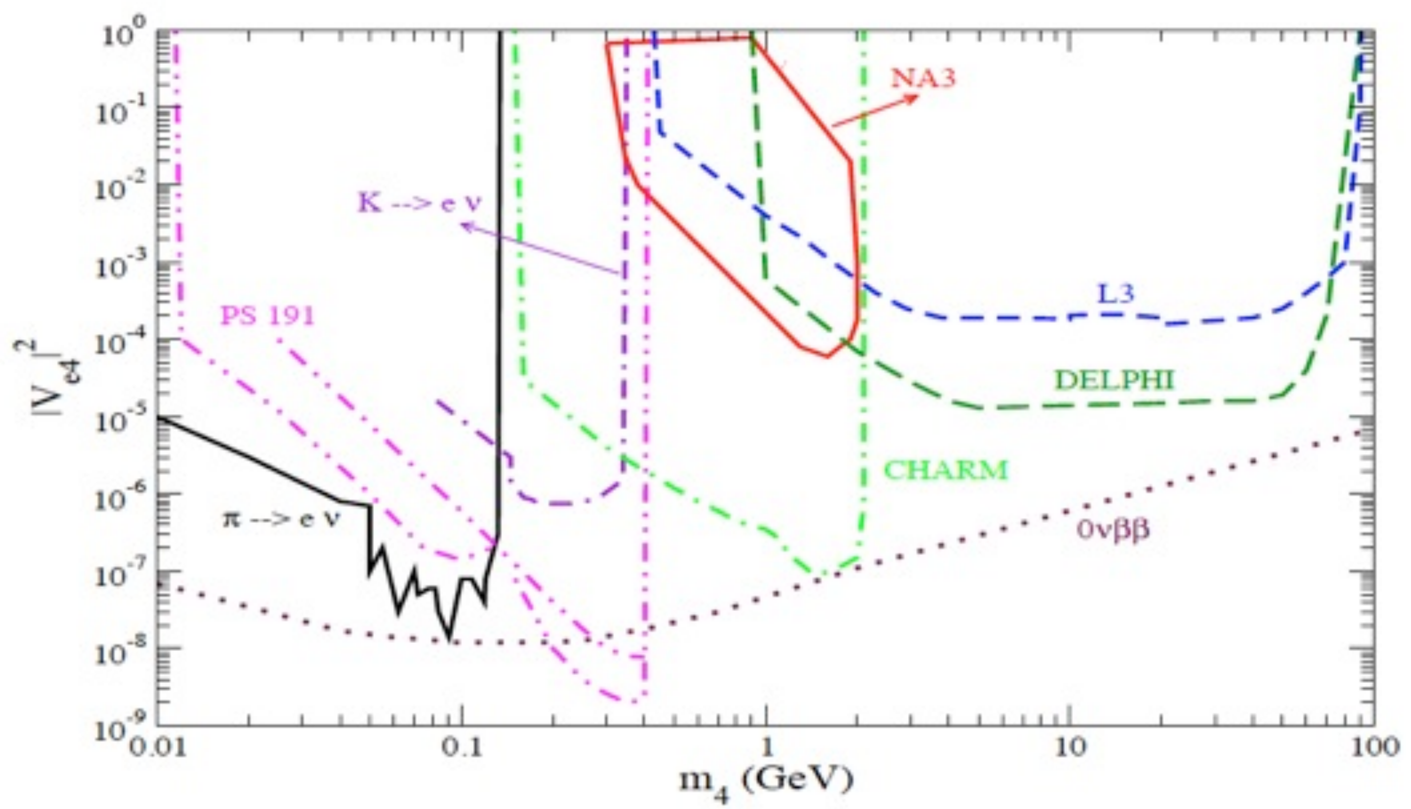
- Neutrino masses
- Peak searches
- Dark Matter, WDM, HDM
- Nu oscillations
- Kinks in beta decay
- Neutrinoless double beta decay

Below the electroweak scale

Low energy see-saw: sterile neutrinos m<< GeV
Very small Yukawa couplings are required or specific cancellations in the masses (inverse or extended see-saw).

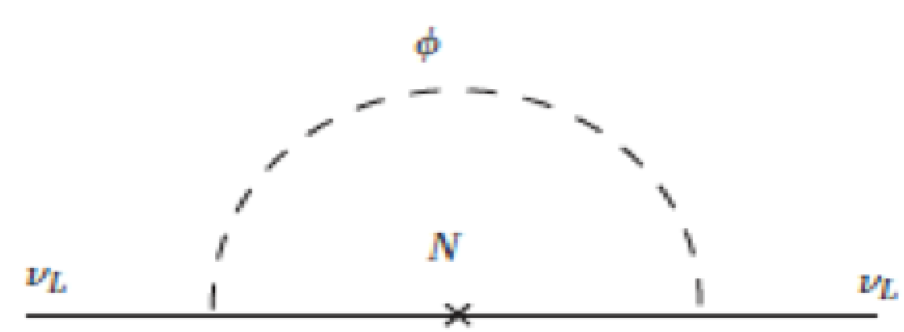


Light sterile neutrinos: a White Paper, 1204.5379



Atre et al., 0901.3589

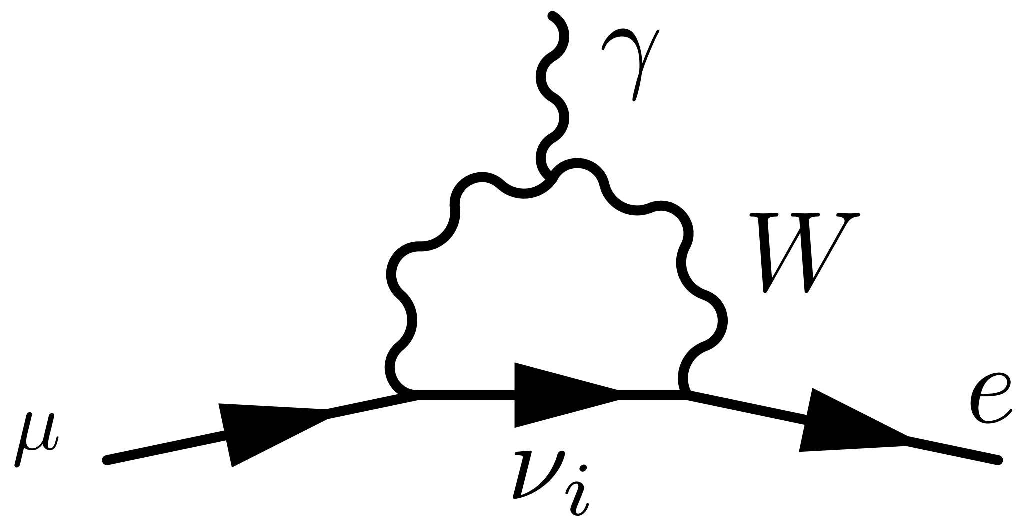
If neutrino masses emerge via loops, in models in which Dirac masses are forbidden, the scale can be lower than in the see-saw models, even at the MeV.



Charged lepton flavour violation

Establishing the origin of neutrino masses requires to have as much information as possible about the masses and to combine it with other signatures of the models (proton decay, LHC searches, LFV, sterile neutrinos, ...).

CLFV plays a special role. Neutrino masses induce LFV processes but they are very suppressed.

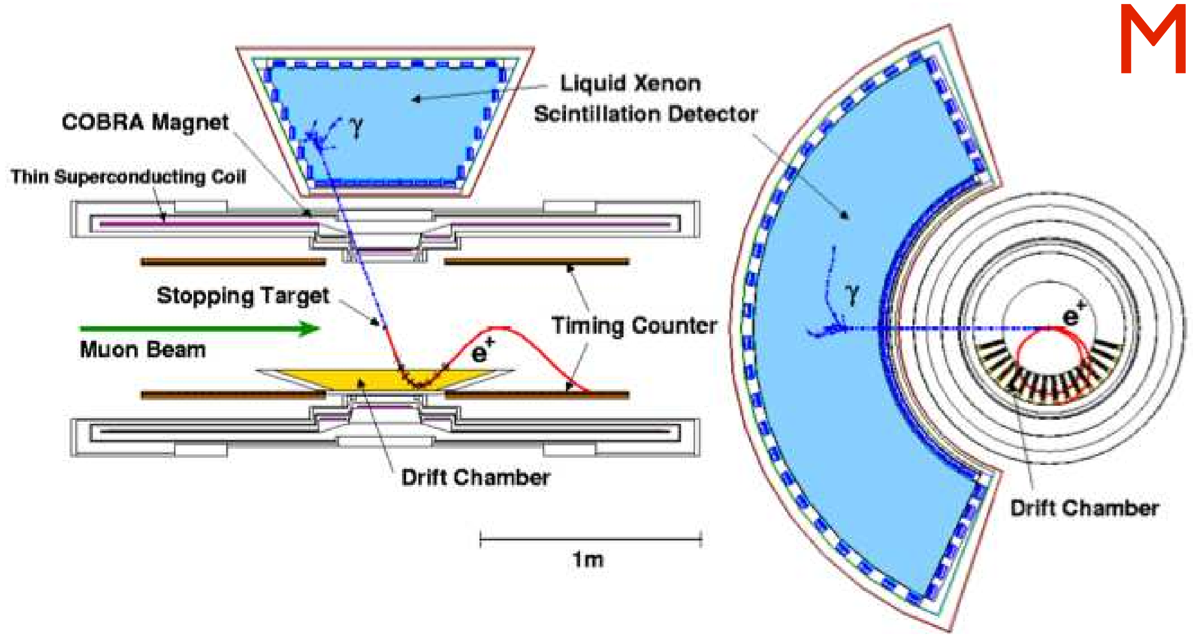


$$Br(\mu \to e\gamma)$$

$$\sim \frac{3\alpha}{32\pi} \left(\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta^2 m_{i1}}{m_W^2}\right)^2 \sim 10^{-53}$$

Many models of neutrino masses give raise to sizable LFV: models at the TeV scale with large mixing (e.g. Inverse seesaw), Radiative neutrino mass models, SUSY GUT see-saw models, Extra D, extra Higgs etc.

MEG at PSI



$$B(\mu \to e\gamma) < 5.7 \times 10^{-13} \quad (90\% \text{ C.L.})$$

MEG: 1303.0754

COherent Muon to Electron Transition (COMET) and PRISM

Limits from SINDRUM-II.

Super-B factories can improve on rare tau decays.

Mu2e: http://mu2e.fnal.gov/

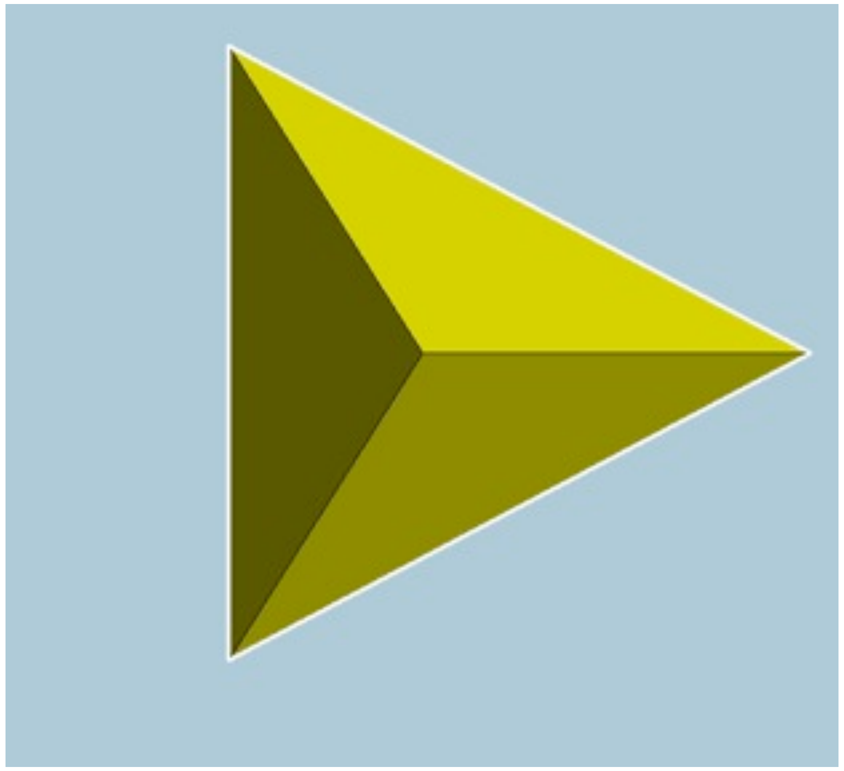
Colliders	CLFV	What Does it Mean?
YES	YES	New Physics at the TeV Scale; Info on Flavor Sector!
YES	NO	New Physics at the TeV Scale; New Physics Very Flavor Blind. Why?
NO	YES	New Physics "Leptonic" or Above TeV Scale; Which one?
NO	NO	No New Physics at the TeV Scale; CLFV only way forward?

Thanks to A. de Gouvea

Any observation of LFV would indicate new physics BSM and provide clues about the origin of neutrino masses.

The problem of flavour

Mixing in the leptonic sector is very different from the quark one: angles are large (even θ_{13} !) and there can be new sources of CP-violation. Neutrinos provide a different perspective on the flavour problem.



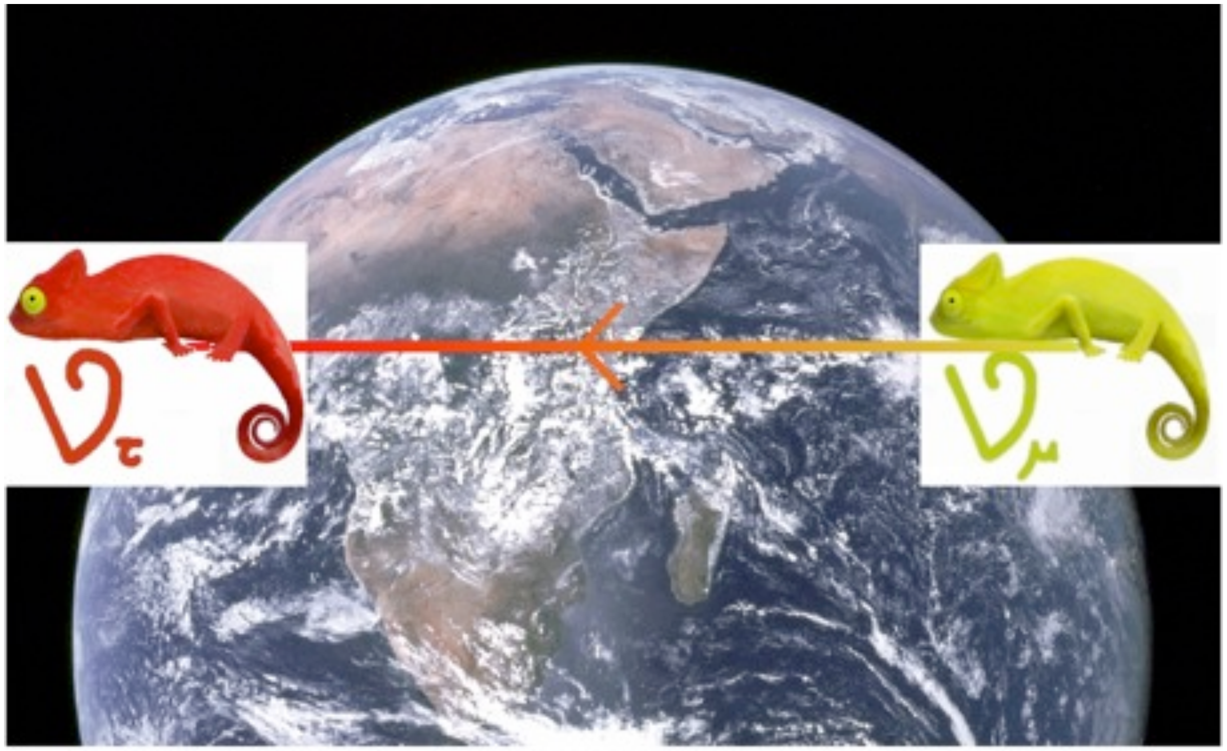
Why three generations?

Why the angles have the values measured?

What is the origin of CPV?

Various approaches can be adopted: Flavour symmetries; Anarchy; Quark-lepton complementarity...
It is crucial to measure with precision the mixing parameters to unveil any underlying pattern.

Conclusions



The discovery of neutrino oscillations has opened a new perspective: neutrino have masses and mix implying new physics beyond the Standard Model of Particle Physics.

A wide experimental programme is taking place: in 2012 we had the discovery of the missing third mixing angle.

The ultimate goal is to understand the origin of neutrino masses (and the new physics scale) and of mixing.

Neutrinos will help to open a new window on the fundamental laws of nature, its constituents and the evolution of the Universe.