

News in ν physics

P. Hernández
CERN and U. Valencia

Introduction

LEP era has established the validity of the Standard Model (SM) based on the gauge group

$$SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times U(1)_{EM}$$

below the 1% level!

The discovery of the last missing particles: t , ν_τ has confirmed the family structure:

| $(1, 2)_{-\frac{1}{2}}$ | $(3, 2)_{-\frac{1}{6}}$ | $(1, 1)_{-1}$ | $(3, 1)_{-\frac{2}{3}}$ | $(3, 1)_{-\frac{1}{3}}$ |
|--|--|---------------|-------------------------|-------------------------|
| $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$ | $\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$ | e_R | u^i_R | d^i_R |
| $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$ | $\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$ | μ_R | c^i_R | s^i_R |
| $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$ | $\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$ | τ_R | t^i_R | b^i_R |

ν are the most elusive particles of the MSM:

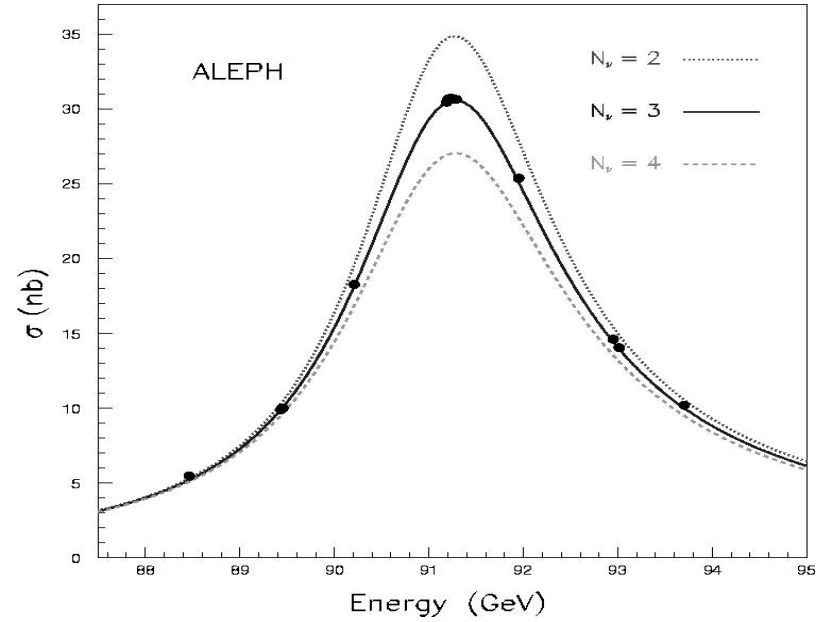
$$m_\nu \simeq 0, \quad Q_{em} = 0, \quad Q_{color} = 0, \quad Q_{SU(2) \times U(1)/U(1)_{em}} \neq 0$$

Instead they have provided essential information on the two most striking features of the fermionic content of the SM:

- Left-handedness of the weak interactions
- The family structure

The Z^0 decays invisibly into exactly three ν :

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_{\nu\bar{\nu}}} = 2.984 \pm 0.008$$



For $v \rightarrow c$:

$$Q_{SU(2)} \neq 0$$

L



$$Q_{SU(2)} = 0$$

R



\vec{p}

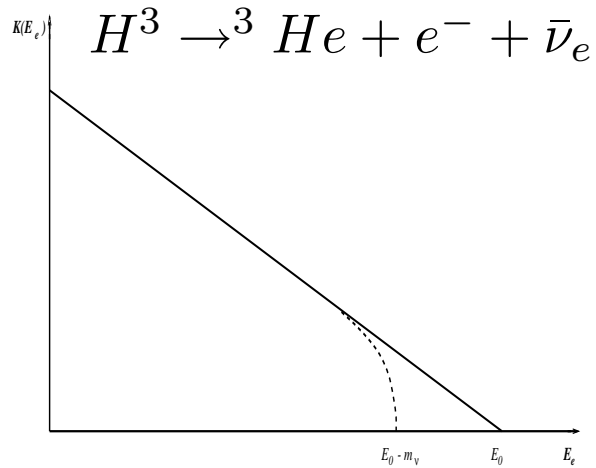
\vec{s}

$CPT \leftrightarrow$ Lorentz invariance \oplus unitarity: is an essential building block of field theory

CPT : L particle \leftrightarrow R antiparticle

Neutrinos in the MSM are massless and exist only in two states: particle with negative helicity and antiparticle with positive one

When the SM was invented there were only upper bounds on the ν masses from weak decay kinematics and these were conjectured to be zero.



$$m_{\nu_e} < 2.2\text{eV (Mainz-Troisk)}$$

$$m_{\nu_\mu} < 170\text{keV (PSI: } \pi^+ \rightarrow \mu^+ \nu_\mu)$$

$$m_{\nu_\tau} < 18.2\text{MeV (ALEPH: } \tau^- \rightarrow 5\pi \nu_\tau)$$

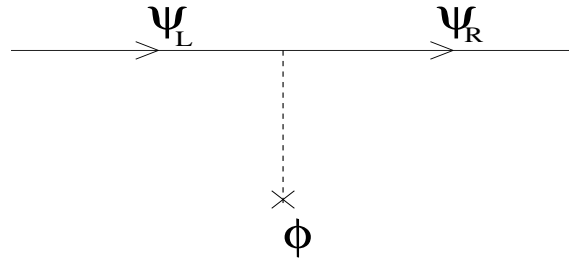
$$K(E_e) \propto \sqrt{(E_0 - E_e)((E_0 - E_e)^2 - m_\nu^2)^{1/2}}$$

Fermion masses

A mass can be thought of as a $L \leftrightarrow R$ transition:

$$m \bar{\psi}_R \psi_L + h.c.$$

In the SM fermion masses originate in the interaction with the Higgs field:



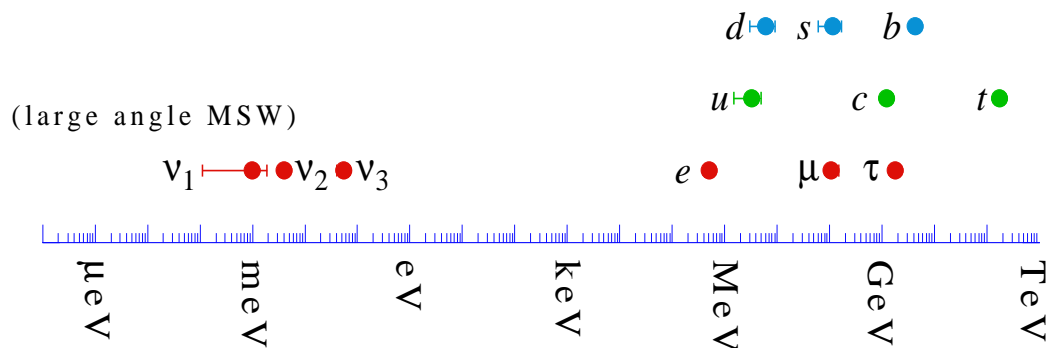
$$\lambda_f \bar{\psi}_R \Phi \psi_L + h.c. \rightarrow m_f = \lambda_f v$$

ν masses: I. Dirac way

ν masses can be easily added to the MSM in the same way as for the remaining leptons: including three singlets, $(\nu_\alpha)_R, \alpha = e, \mu, \tau$ with $Q_{SU(3)} = Q_{SU(2)} = Q_{U(1)} = 0$ and proceed like for the quarks and charged leptons:

$$m_\nu = \lambda_\nu v \quad \lambda_\nu \ll \lambda_l$$

- New hierarchy problem: why $m_{\nu_i} \ll m_{l_i}$?



- $B - L$ is an exactly conserved global symmetry ($B + L$ broken non-perturbatively):

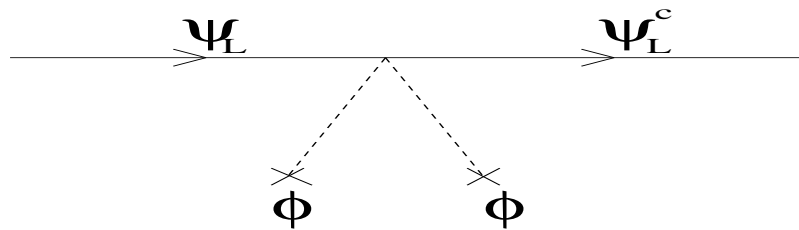
$$B : \Psi_q \rightarrow e^{i\alpha/3} \Psi_q \quad L : \Psi_l \rightarrow e^{i\alpha} \Psi_l$$

ν masses: II. Majorana way

$CPT \leftrightarrow$ L particle \leftrightarrow R antiparticle

For neutral fermions, Majorana realized that one can get rid of half of the degrees of freedom in a massive Dirac spinor by identifying:

$$\psi = \psi_L + \psi_R \quad \psi_R \rightarrow (\psi_L)^c = C\bar{\psi}_L^T$$



In the SM one can indeed write a $L \leftrightarrow R$ coupling of this form in a gauge invariant way:

Weinberg

$$\frac{\alpha_\nu}{M} \nu_L^T C \tilde{\Phi}^T \tilde{\Phi} \nu_L + h.c. \rightarrow m_\nu = \alpha_\nu \frac{v^2}{M}$$

If $M \gg v$ neutrinos will be naturally much lighter than the remaining fermions!

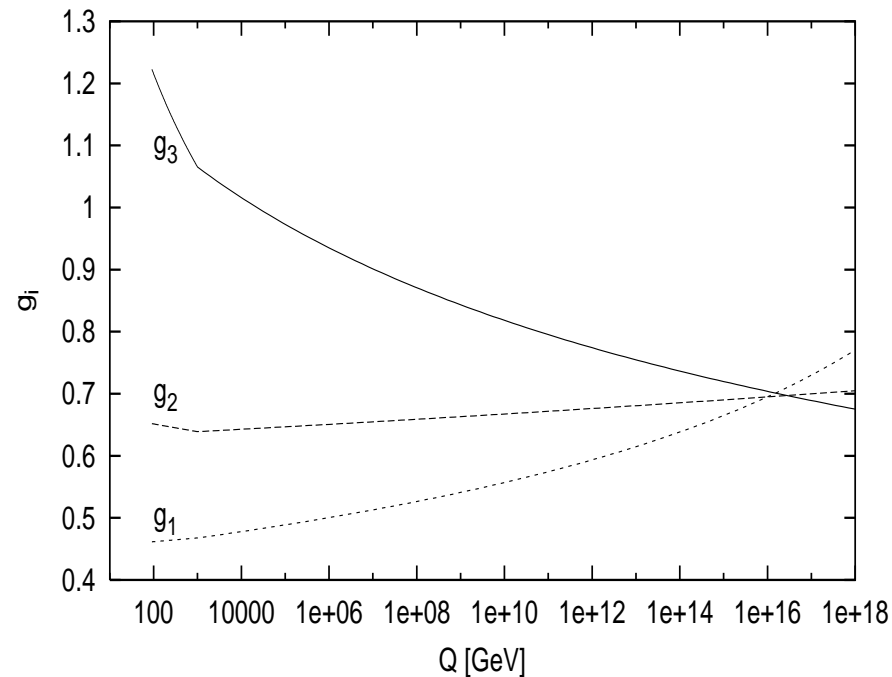
The consequences of the Majorana alternative are profound:

- **Physics beyond the SM** at a scale M !

Data imply there is at least one $m_\nu \geq 0.05\text{eV}$. If $\lambda_\nu \sim O(1)$:

$$v < M \sim 10^{15}\text{GeV} < M_{Planck}$$

Intriguingly close to the typical Grand Unification (GUT) scale !



- Majorana fermions carry no conserved global charge: L is violated at the classical level !

$$\nu_L \rightarrow e^{i\alpha} \nu_L \quad \text{not a symmetry}$$

The scale M is the scale of lepton number violation

- Consistency of the theory with the matter content of the SM implies electromagnetic charge quantization !

ν -masses are not just the last fundamental parameters in the SM to add to the Particle Data Book...

- If they are Majorana they provide a window into a new physics scale which might give us a clue on the origin of fermion masses (flavour sector): $\{\lambda_f\} \rightarrow 22/26$ parameters of the SM

why 3 families ? why is there a hierarchy between them ?

- Big Bang nucleosynthesis is very sensitive to the number of light neutrino species. After WMAP:

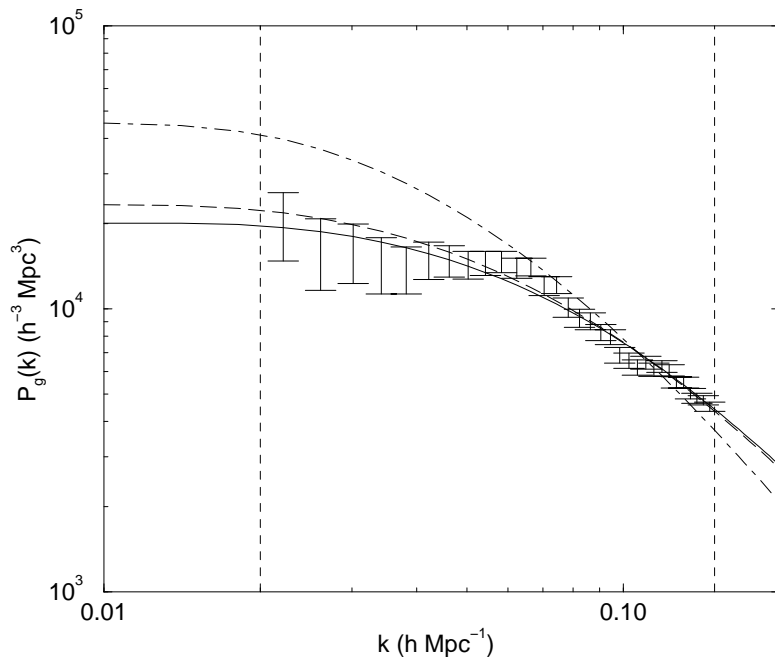
$$N_\nu < 3.4(95\%CL)$$

Pierce, Murayama

- they contribute to the energy density of the Universe (\rightarrow large scale structure...)
- Lepton number violation provides a simple mechanism to explain the observed baryon asymmetry in the Universe \rightarrow leptogenesis

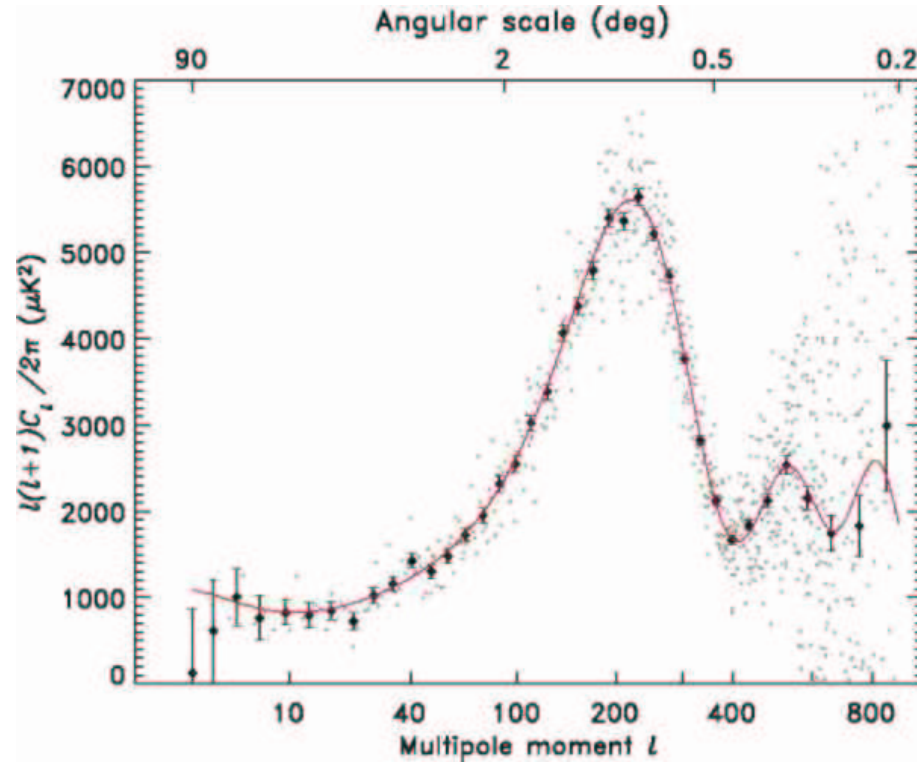
Neutrino properties CMB and large scale structure

2dFGRS *Elgaroy et al*



$$\sum_i m_i \leq 1.8\text{eV}$$

WMAP *Spergel et al*



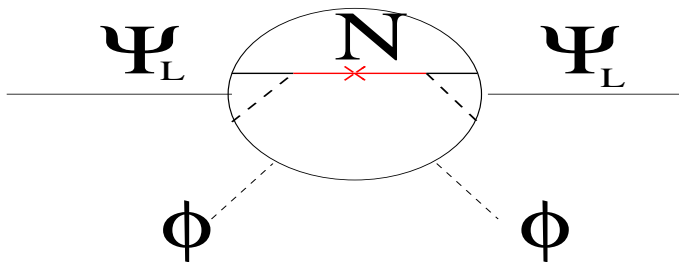
$$\sum_i m_i \leq 0.69\text{eV (95\%CL)}$$

Leptogenesis

Fukugita, Yanagida

Gell-Mann, Ramond, Slansky, Yanagida

See-saw model:



$M \rightarrow$ mass of the heavy Majorana neutrinos

The three conditions of Sakharov for producing a lepton number out of a symmetric initial state are met in the decay of the N 's:

- Decay out of equilibrium if $T_D \sim M_N \Gamma_N \ll$ rate of expansion
- L violation: $\Gamma(N \rightarrow \Phi l), \Gamma(N \rightarrow \Phi \bar{l}) \neq 0$
- CP-violation: $\epsilon_{CP} = \frac{\Gamma(N \rightarrow \Phi l) - \Gamma(N \rightarrow \Phi \bar{l})}{\Gamma(N \rightarrow \Phi l) + \Gamma(N \rightarrow \Phi \bar{l})} \neq 0 \Rightarrow \Delta L$ created in decay

- $\Delta B \sim \Delta L$ because $B + L$ -violating processes: are in equilibrium for $T > 100\text{GeV}$

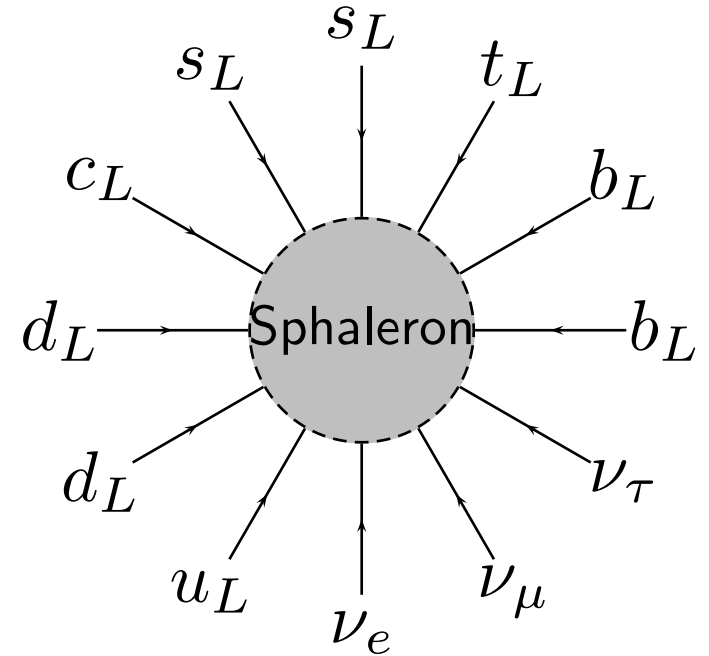
t'Hooft; Kuzmin, Rubakov, Shaposnikov

Final asymmetry:

$$Y_B = 10^{-2} \underbrace{\epsilon_{CP}}_{\text{CP-asym}} \underbrace{\kappa}_{\text{eff. factor}}$$

κ efficiency factor which depends on the non-equilibrium dynamics.

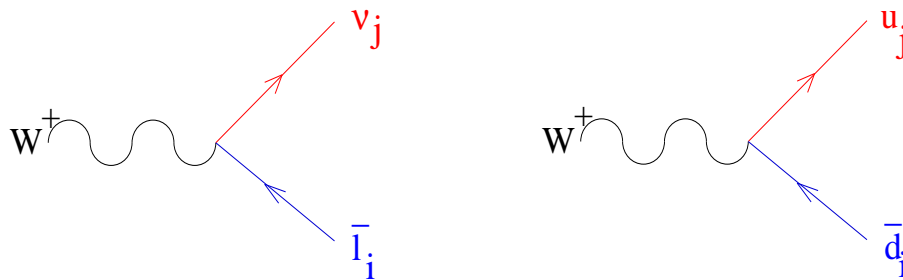
Details are model dependent because the CP-asymmetry cannot be predicted only from the low-energy parameters, but there is a large range of *natural* parameters where the observed $n_B/n_\gamma \sim 6 \times 10^{-10}$ can be obtained



Neutrino masses and mixing

If the fermions have a mass the charged current interactions are not flavour diagonal: there is mixing among the families Pontecorvo; Maki, Nakagawa, Sakata

$$\frac{g}{\sqrt{2}} W_{\mu}^{+} \sum_{ij} (V_{NMS}^{ij} \bar{l}_L^i \gamma_{\mu} \nu_L^j + V_{CKM}^{ij} \bar{U}_L^i \gamma_{\mu} D_L^j) + h.c.$$



$$\begin{pmatrix} \nu_e \\ \nu_{\mu} \\ \nu_{\tau} \end{pmatrix} = V_{MNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

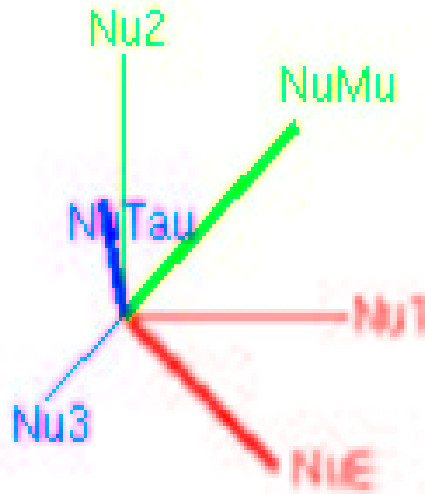
The MNS matrix has four physical parameters:

| | Angles | Phases |
|----------|--------|--------|
| Dirac | 3 | 1 |
| Majorana | 3 | 3 |

Phases \rightarrow CP-violation

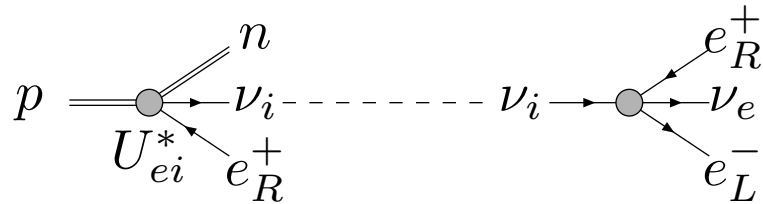
$$V_{MNS}^{\text{Dirac}} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12}e^{i\delta} & 0 \\ -s_{12}e^{i\delta} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V_{MNS}^{\text{Majorana}} = V_{MNS}(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$



Neutrino oscillations

Pontecorvo



Neutrinos produced in a flavour eigenstate can change flavour as they propagate:

$$x = 0 \quad |\nu_\alpha\rangle = \sum_j V_{\alpha j} |\nu_j\rangle \Rightarrow |\nu_\alpha(x)\rangle = \sum_j V_{\alpha j} e^{iEt} e^{ixp_j} |\nu_j\rangle$$

Vacuum oscillations ($W_{\alpha\beta}^{jk} \equiv [V_{\alpha j} V_{\beta j}^* V_{\alpha k}^* V_{\beta k}]$)

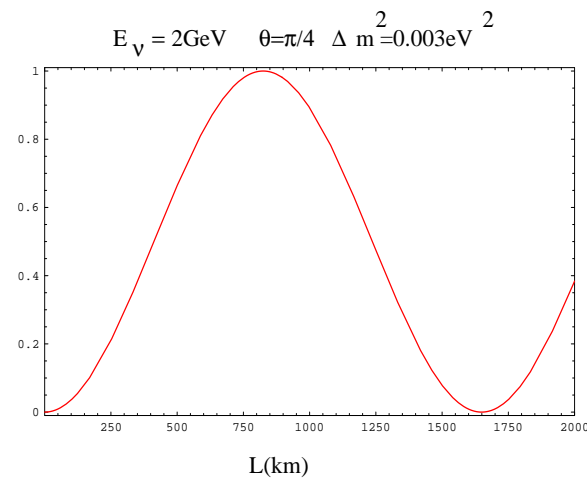
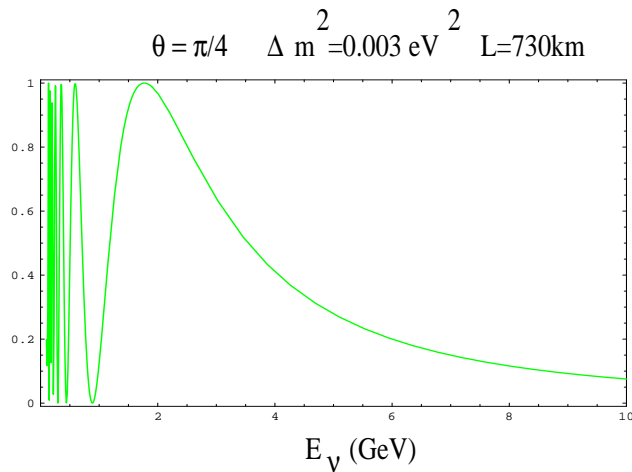
$$|\langle \nu_\beta | \nu_\alpha(L) \rangle|^2 = P(\nu_\alpha \rightarrow \nu_\beta) = -4 \sum_{k>j} \text{Re}[W_{\alpha\beta}^{jk}] \sin^2 \left(\frac{\Delta m_{jk}^2 L}{4E_\nu} \right) \pm 2 \sum_{k>j} \text{Im}[W_{\alpha\beta}^{jk}] \sin \left(\frac{\Delta m_{jk}^2 L}{2E_\nu} \right)$$

For 2 families: $V_{MNS} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E_\nu} \right) \rightarrow \text{appearance}$$

$$P_{\alpha\alpha} = 1 - P_{\alpha\beta} < 1 \rightarrow \text{disappearance}$$

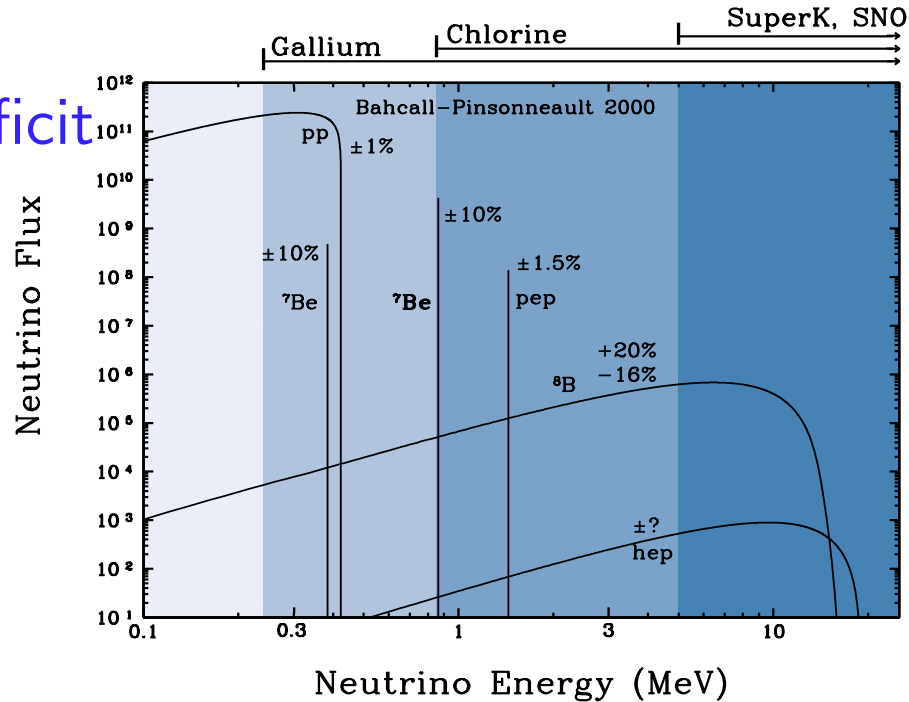
$$L_{\text{osc}}(\text{km}) = 2\pi \frac{E_\nu(\text{GeV})}{1.27 \Delta m^2(\text{eV}^2)}$$



- Independent on absolute ν mass scale and "Majoraneness"
 - Smoking guns for neutrino oscillations are:
 1. flavour transitions \rightarrow need experiments that can tell flavour
 2. the L/E_ν dependence \rightarrow need experiments with $L \sim L_{osc}(E_\nu)$
- $L \gg L_{osc}$: $\langle P(\nu_\alpha \rightarrow \nu_\beta) \rangle = \frac{1}{2} \sin^2 2\theta$ (averaged oscillations)

Evidence for neutrino oscillations

The solar puzzle ν_e deficit



Long history...

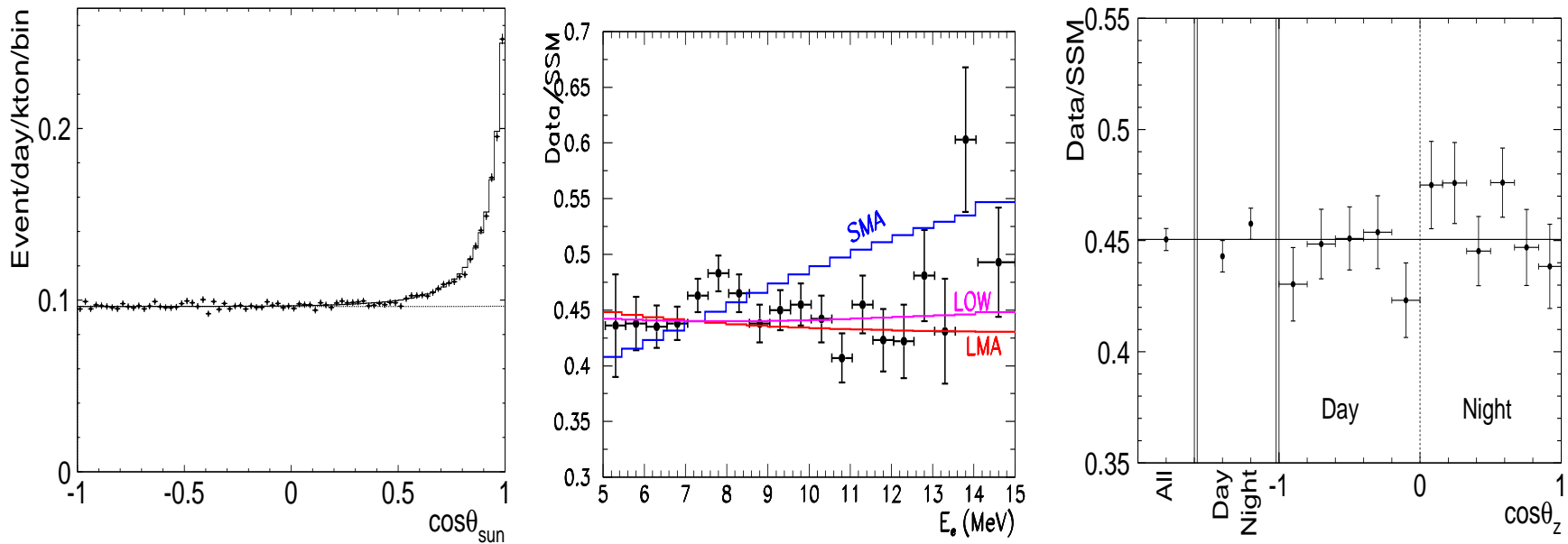
| Exp. | Tech. | E_ν^{th} | data/SSM |
|----------------------------|---|--------------|----------|
| Homestake ('68) | ${}^{37}\text{Cl}(\nu, e^-) {}^{37}\text{Ar}$ | > 0.81 MeV | 0.30(5) |
| Gallex \oplus Sage ('90) | ${}^{71}\text{Ga}(\nu, e^-) {}^{71}\text{Ge}$ | > 0.23 MeV | 0.58(6) |
| K \rightarrow SK ('95) | Cerenkov | > 6.5 MeV | 0.39(6) |
| SNO ('99) | Cerenkov | > 6.75 MeV | 0.29(5) |

Recent achievements: towards an oscillation signal independent on the theoretical input on the solar model !

The three recent milestones

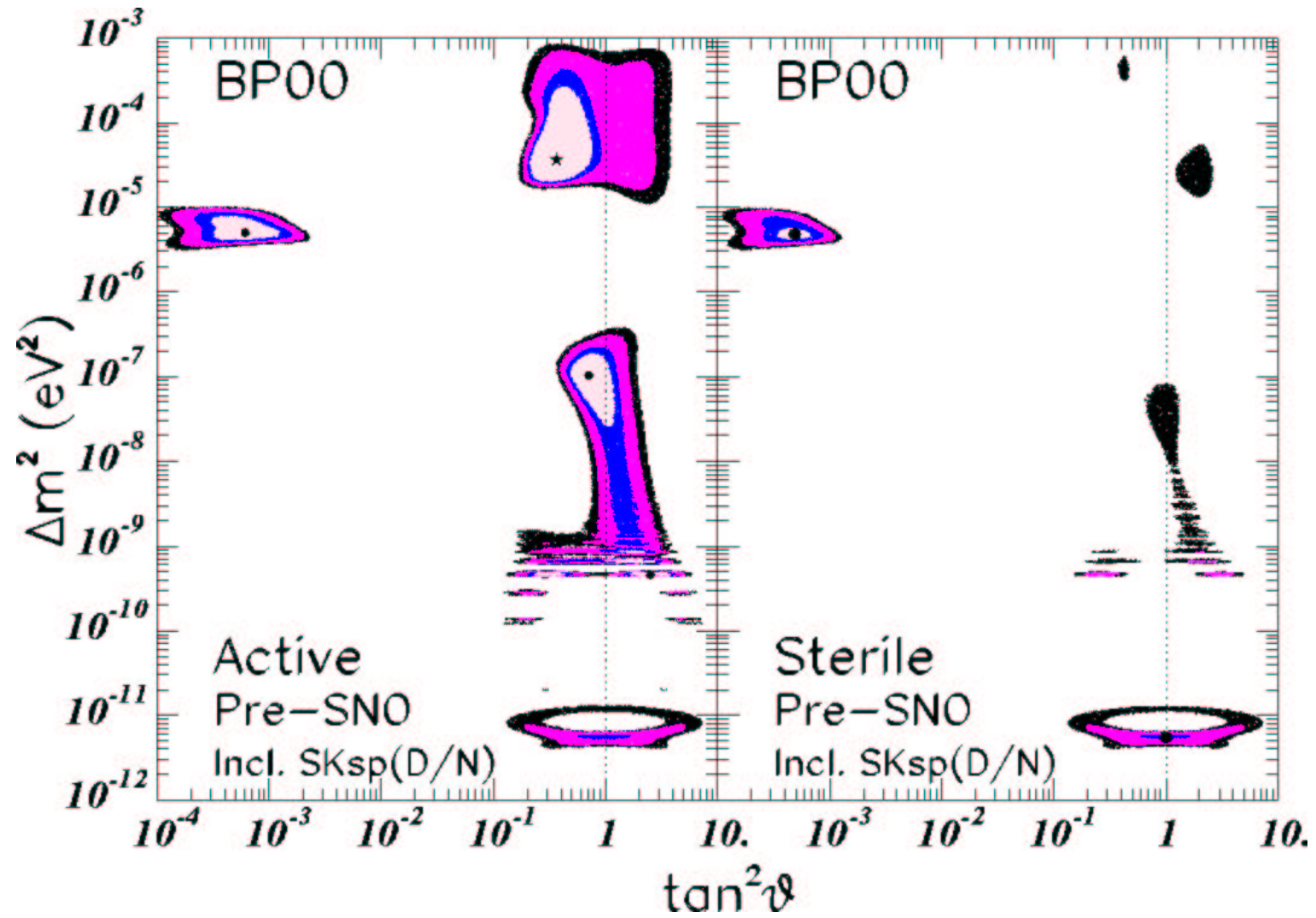
- **SuperKamiokande (1998): $\nu_e + e^- \rightarrow \nu_e + e^-$**

Get information on direction and energy of the ν 's !



The neutrinos definitely come from the Sun, no spectral distortion and no significant day-night asymmetry

Global Fits 2000



- SNO (2001):

$$(CC) \quad \nu_e + d \rightarrow p + p + e^- \quad E_{thres} > 1.4MeV$$

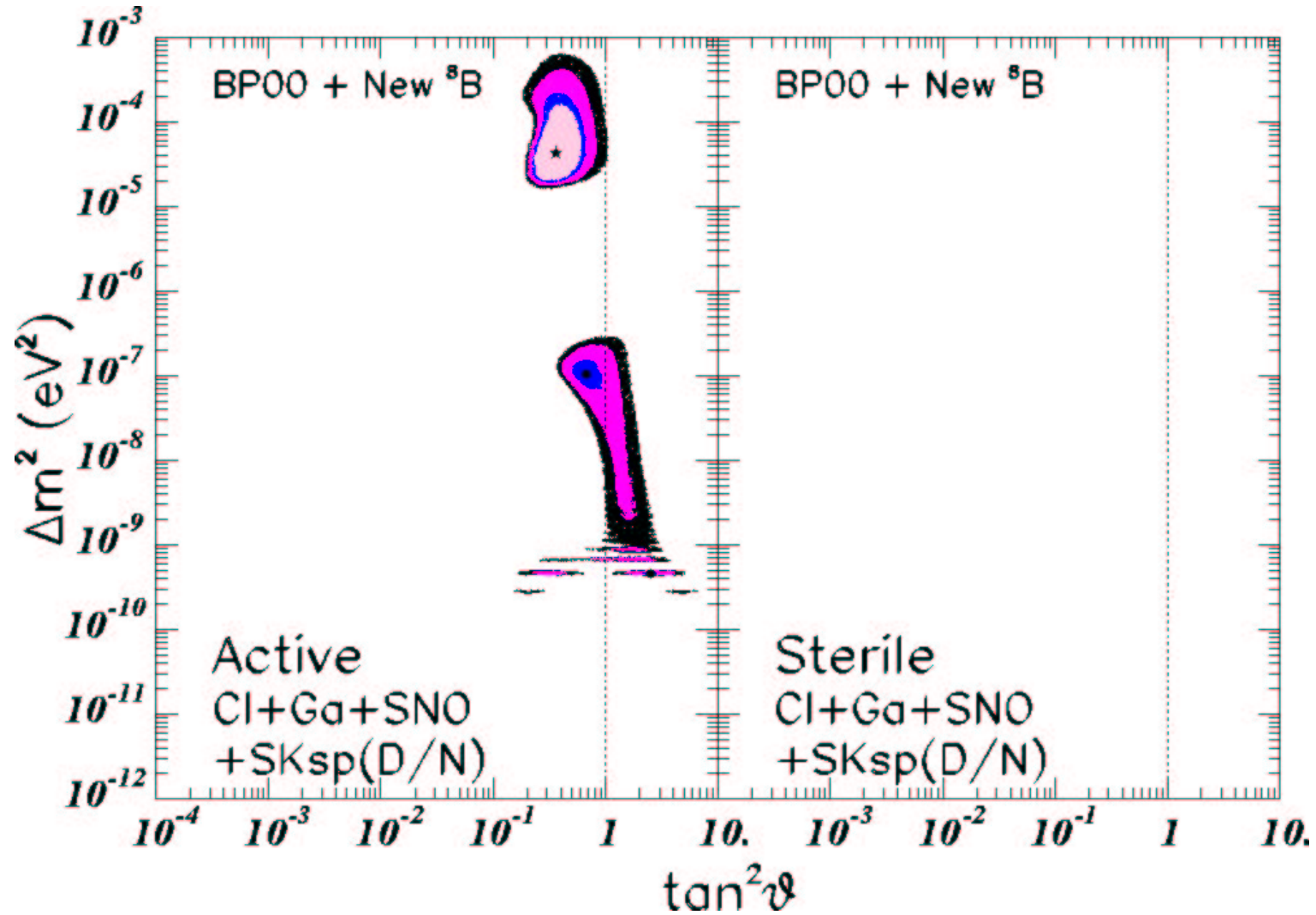
$$(NC) \quad \nu_x + d \rightarrow p + n + \nu_x \quad x = e, \mu, \tau \quad E_{thres} > 2.2MeV$$

$$\phi_{8B}^{SNO-CC} = 1.76_{-0.05}^{+0.06}(\text{stat})_{-0.09}^{+0.09}(\text{syst}) \times 10^6 \text{cm}^{-2} \text{s}^{-1}$$

$$\phi_{8B}^{SNO-NC} = 5.09_{-0.43}^{+0.44}(\text{stat})_{-0.43}^{+0.46}(\text{syst}) \times 10^6 \text{cm}^{-2} \text{s}^{-1}$$

The Sun shines other active species (ν_μ, ν_τ) about two times more than it shines ν_e : the first direct demonstration of flavour transitions in the solar flux!

Global Fits 2002

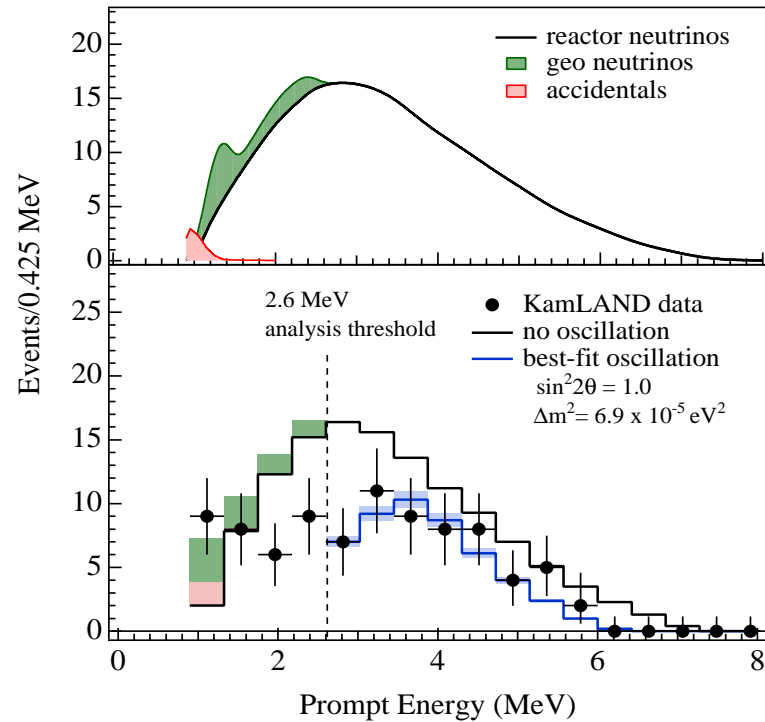
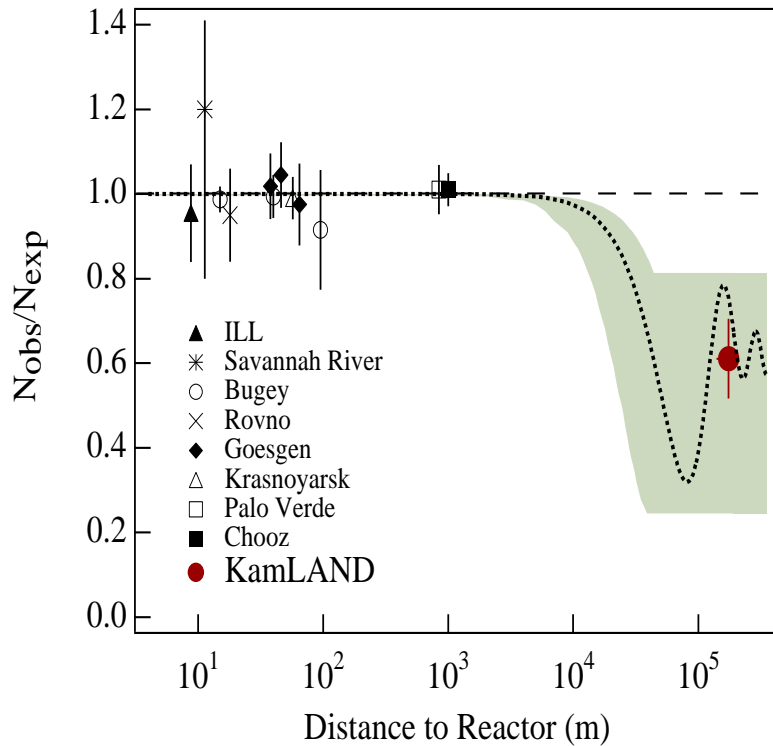


- KamLAND (2002):**

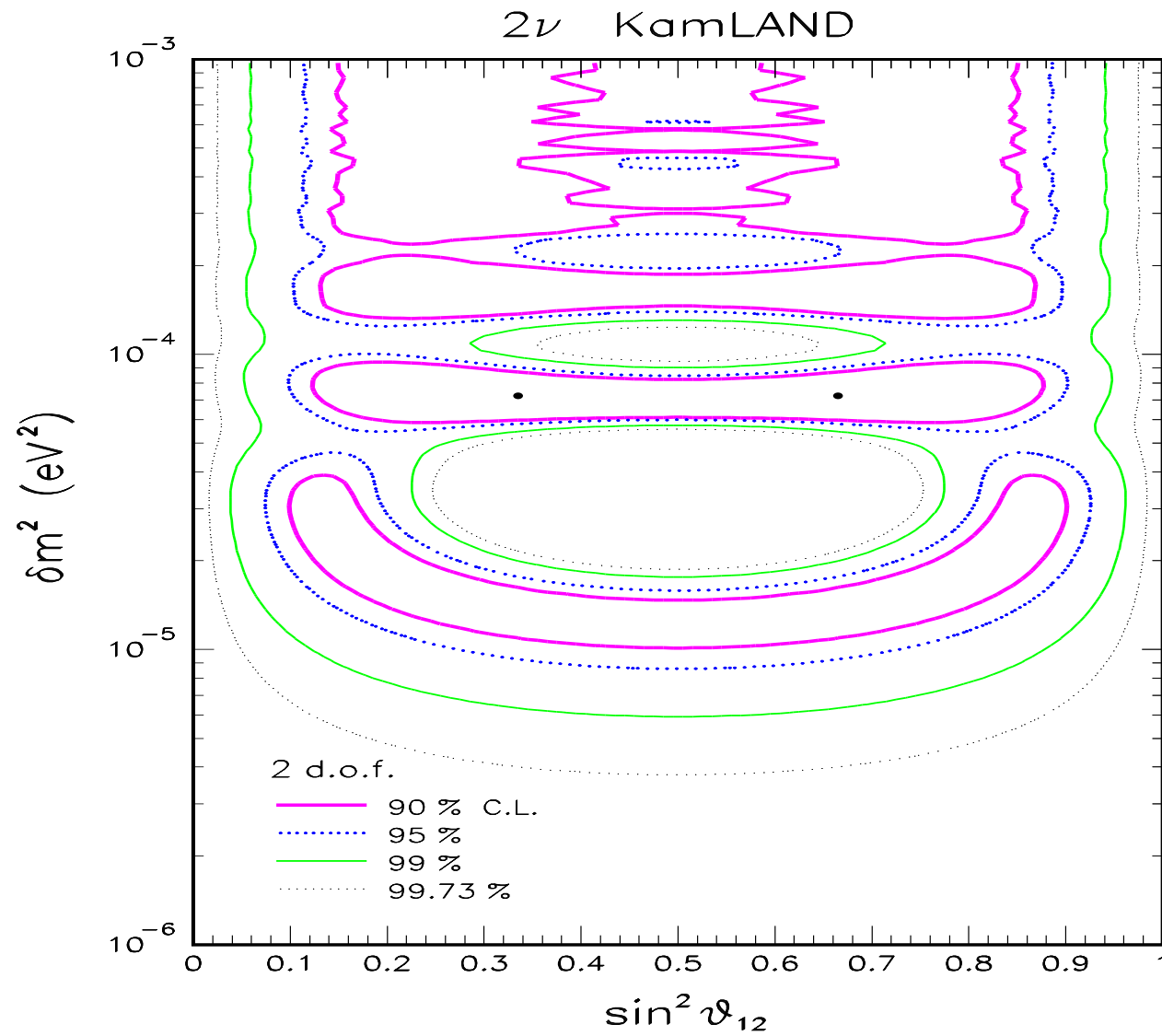
Measures reactor neutrinos from a cluster of nuclear plants around Kamioka

$$\langle L \rangle = O(175) \text{ km}$$

$$\langle E_\nu (\text{MeV}) \rangle / L(100 \text{ km}) \sim 10^{-5} \text{ eV}^2$$

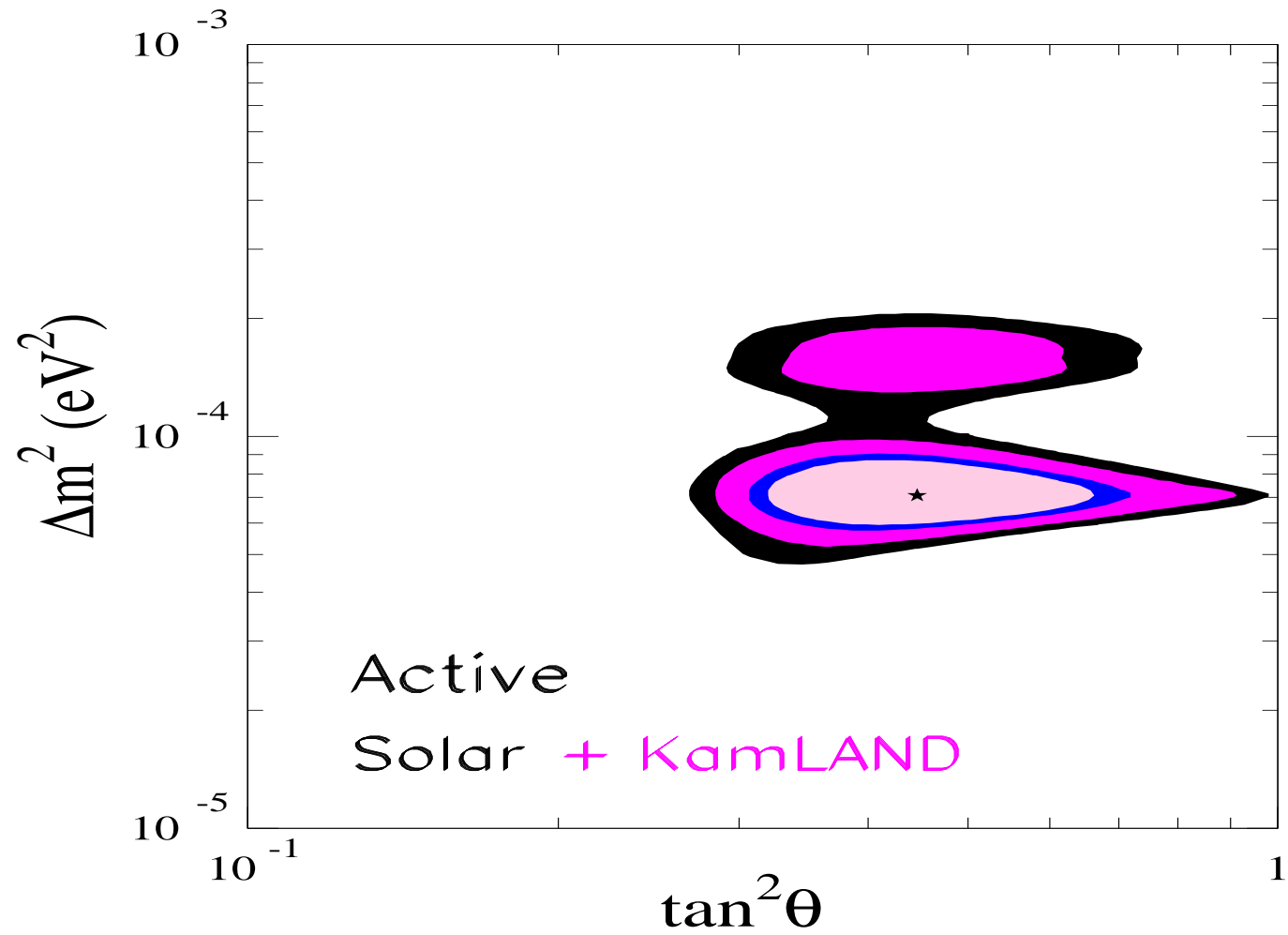


Reactor fluxes contain less $\bar{\nu}_e$ than expected and show the expected E/L dependence: if confirmed first direct proof of oscillations!



Fogli et al

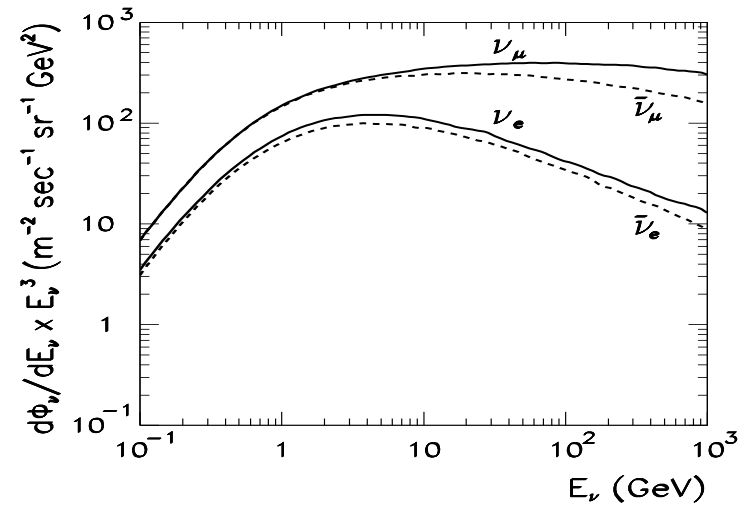
Global Fits 2003



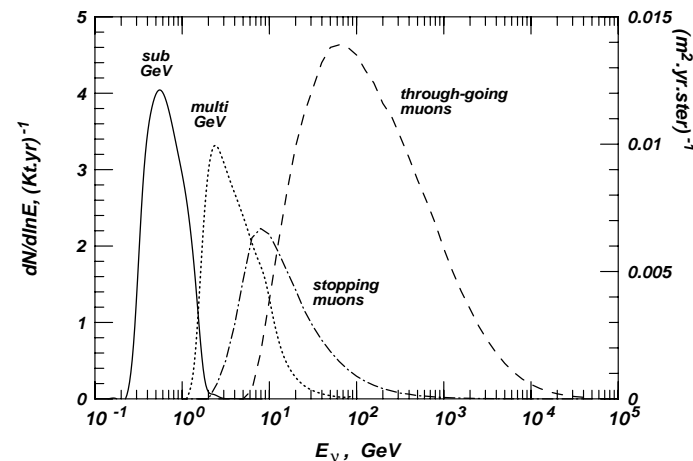
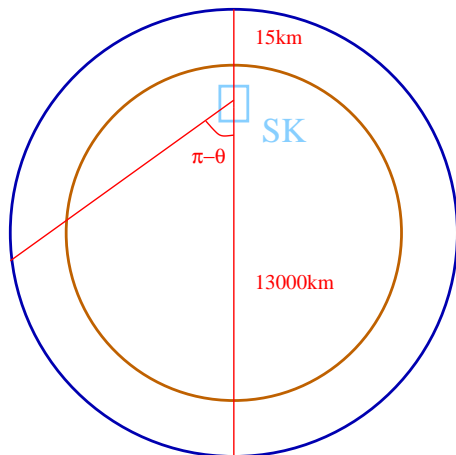
Bahcall et al

Atmospheric ν anomaly

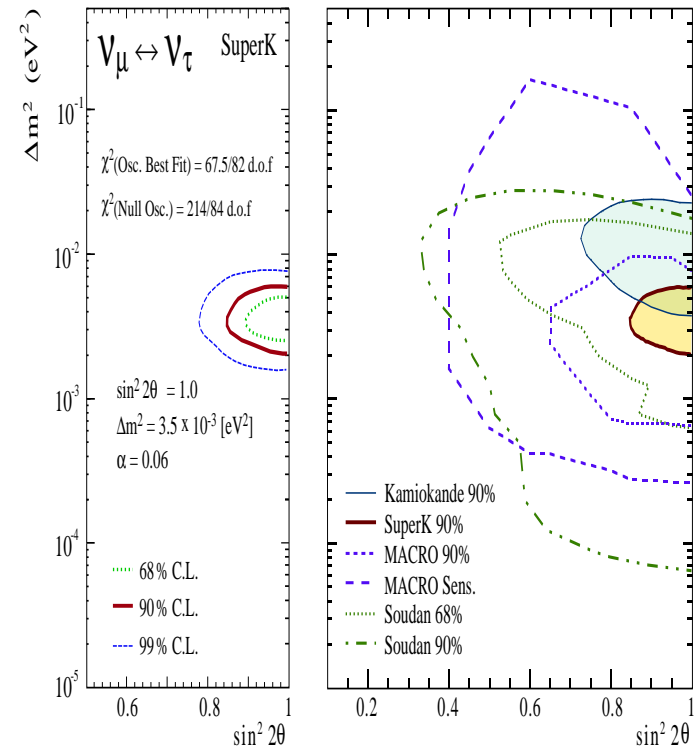
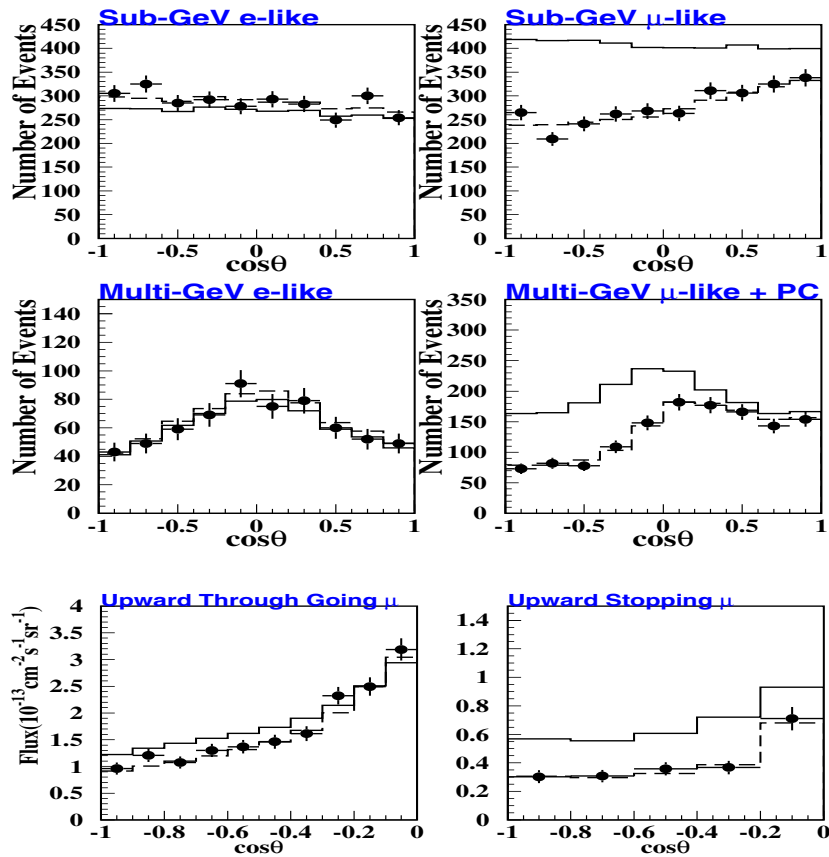
ν are produced in the atmosphere when primary cosmic rays impinge on it producing K, π which subsequently decay:



A deficit was observed in the ratio μ/e events: **Soudan2, IMB, Kamiokande SuperKamiokande (1998)**



Emerging ν oscillation hypothesis: $\nu_\mu \rightarrow \nu_\tau$ (essential Chooz input: $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1!$)

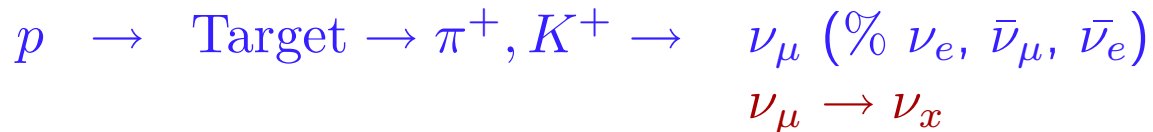


- Less $\nu_\mu/\bar{\nu}_\mu$ than expected from below
- Evidence for the expected E_ν/L dependence

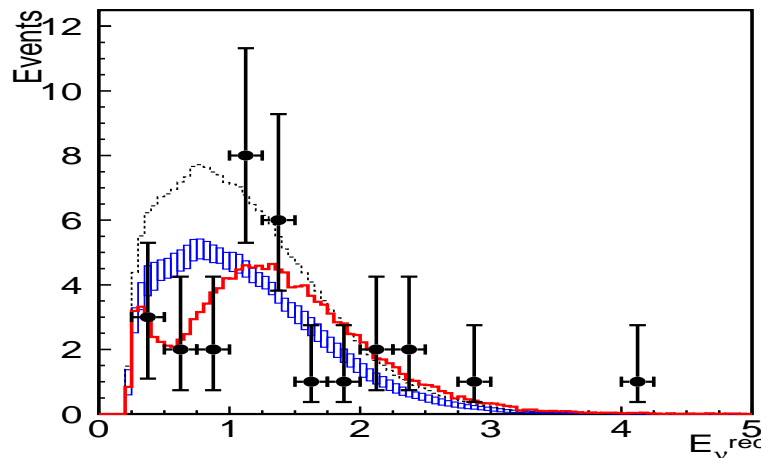
Confirmation of the oscillation hypothesis in "man-made" ν sources

$$|\Delta m_{\text{atmos}}^2| \sim \frac{E_\nu(1 - 10\text{GeV})}{L(10^2 - 10^3\text{km})}$$

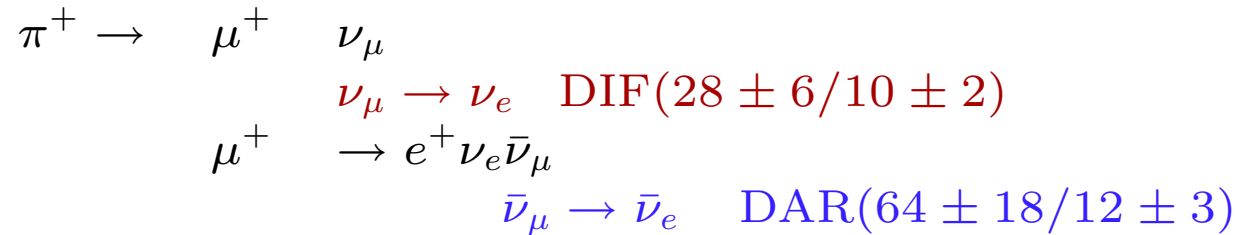
ν beams in this energy range can easily be produced at accelerators



Three such conventional beams **KEK-Kamioka (235km)**, **Fermilab-Soudan (730km)**, **CERN-Gran Sasso (730km)** will search for the disappearance of ν_μ or appearance of ν_τ :

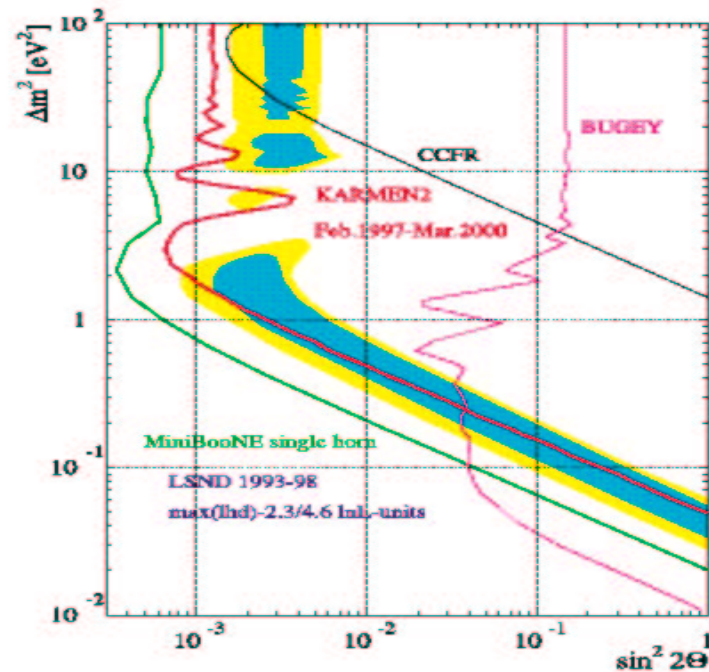


LSND First positive signal of oscillations in a laboratory ν beam:



Best fit: $\Delta m^2 = 1.2 \text{ eV}^2$, $\sin^2 2\theta = 0.003$

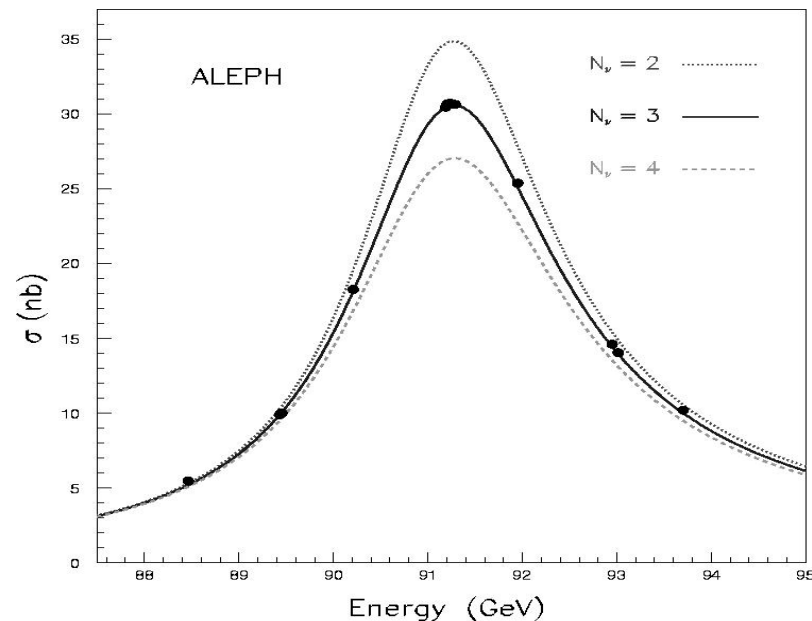
But KARMEN ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) does not confirm this signal



Does all this fit in the SM ?

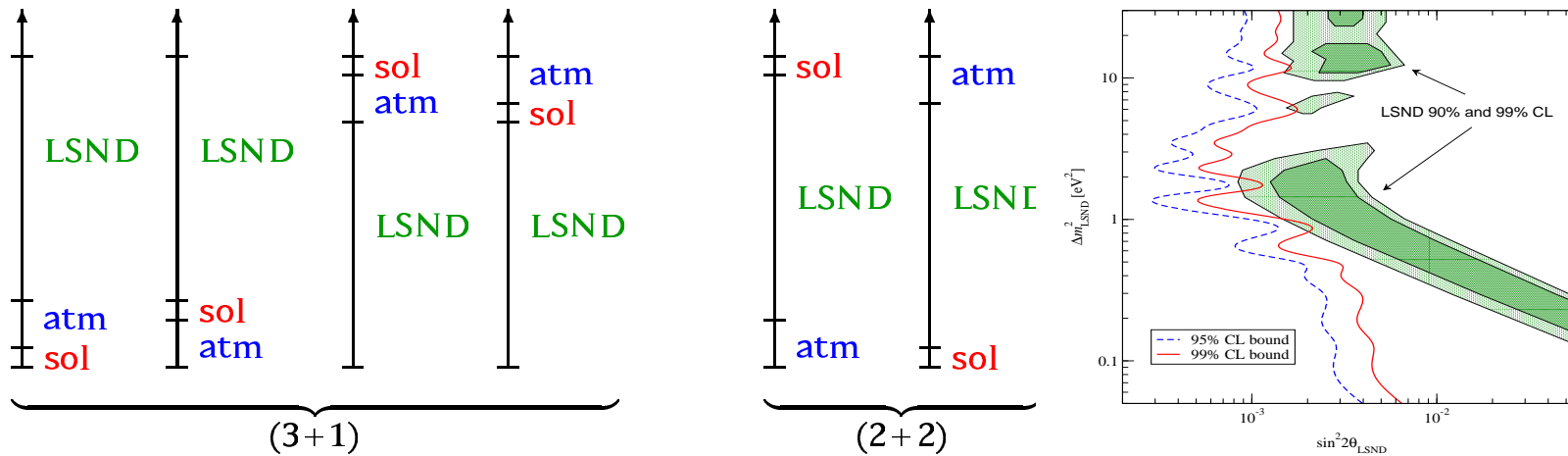
$$|\Delta m_{solar}^2| \ll |\Delta m_{atmos}^2| \ll |\Delta m_{LSND}^2|$$

- The mixing of the three standard neutrinos ν_e, ν_μ, ν_τ can only explain two of the anomalies:
- The explanation of the three set of data requires the existence of a sterile ν species: $N_\nu = 2.984 \pm 0.008$



This hypothesis seems to be in more trouble with new data:

- Global analysis of solar \otimes atmospheric \oplus LSND with 4- ν fit the data poorly



Maltoni et al

- WMAP results: $N_\nu < 4$, $\sum_i m_i < 0.69\text{eV}$

\oplus Theorist prejudice: light sterile neutrinos are monsters of Nature

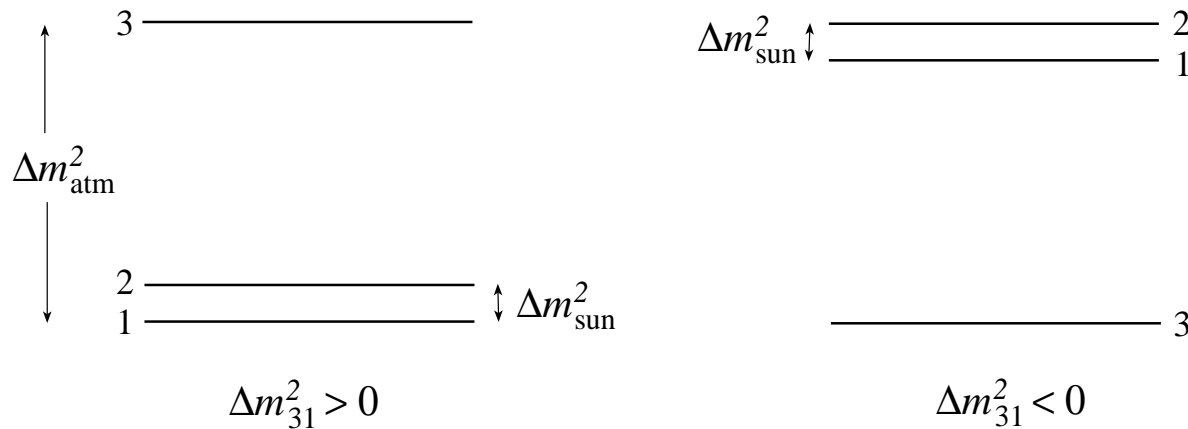
Standard scenario: drop the LSND result \Rightarrow MiniBooNE

Atmos \oplus Solar oscillations in SM with massive neutrinos

Atmos: ($\Delta m_{23}^2 = m_3^2 - m_2^2, \theta_{23}$) Solar: ($\Delta m_{12}^2 = m_2^2 - m_1^2, \theta_{12}$)

$$\Delta m_{23}^2 \sim 2.7 \times 10^{-3} eV^2 \quad \Delta m_{12}^2 \sim 7 \times 10^{-5} eV^2 \quad \theta_{23} \sim 45^\circ \quad \theta_{12} \sim 34^\circ$$

ν spectrum:



ν mixing matrix:

$$V_{MNS} \simeq \begin{pmatrix} \frac{1}{\sqrt{2}}(1 + \lambda) & \frac{1}{\sqrt{2}}(1 - \lambda) & s_{13} \\ -\frac{1}{2}(e^{i\delta}(1 - \lambda) + s_{13}) & \frac{1}{2}(e^{i\delta}(1 + \lambda) - s_{13}) & \frac{1}{\sqrt{2}} \\ \frac{1}{2}(e^{i\delta}(1 - \lambda) - s_{13}) & -\frac{1}{2}(e^{i\delta}(1 + \lambda) + s_{13}) & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

$$\lambda \sim 0.2 \quad \theta_{13} \leq 10^\circ \quad \delta, \alpha_1, \alpha_2 \quad \text{unconstrained}$$

Completing the picture

After the next generation of neutrino experiments we will probably be far from having the complete picture:

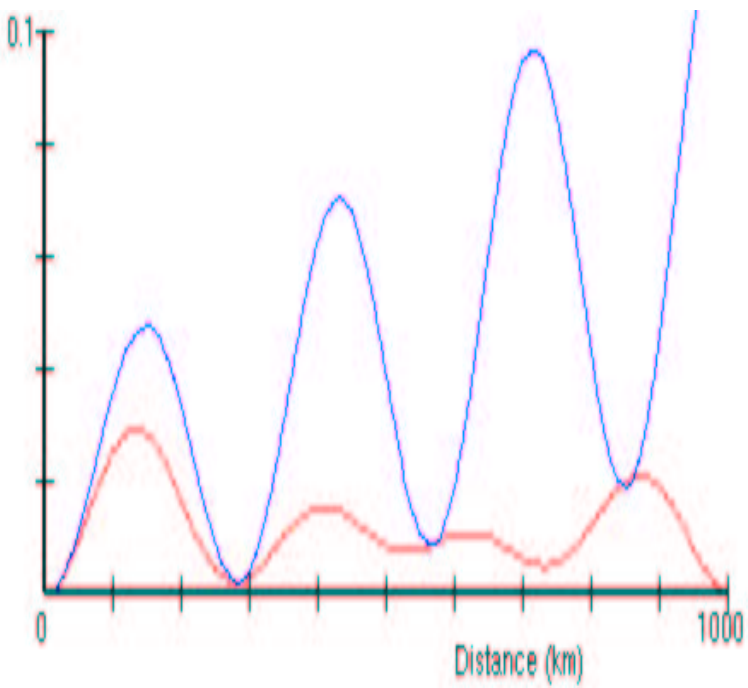
1. Fill in the unknowns of the mixing matrix: θ_{13}, δ
2. Establish if CP violation occurs: ie. $\sin \delta \neq 0$
3. Find the correct spectrum: ie. $\Delta m_{atmos}^2 > \text{or} < 0$



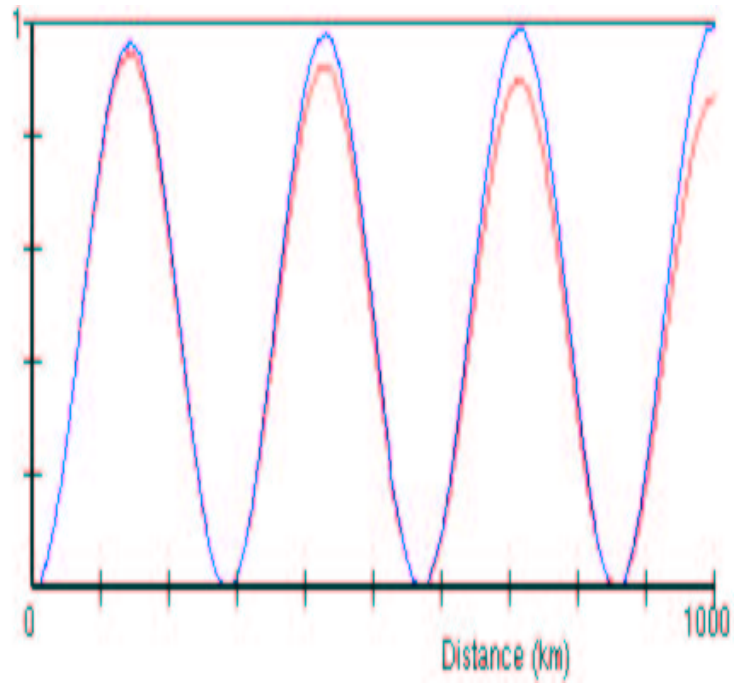
can be achieved in more precise ν experiments which measure for $\langle E_\nu \rangle / L \sim \Delta m_{atmos}^2$, the subleading transitions:

$$\nu_e \leftrightarrow \nu_\mu \text{ and } \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$$

$P_{\nu_e \rightarrow \nu_\mu}$ vs. $P_{\bar{\nu}_e \rightarrow \bar{\nu}_\mu}$



$P_{\nu_\mu \rightarrow \nu_\tau}$ vs. $P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau}$

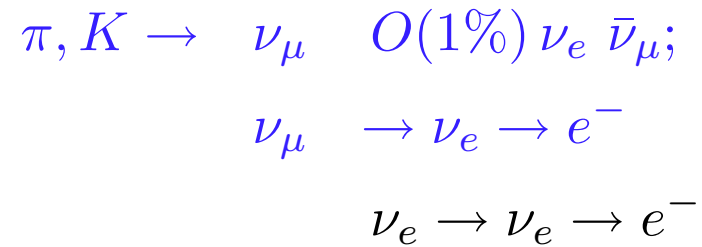


$$E_\nu = 500 \text{ MeV} \quad \theta_{13} = 8^\circ \quad \delta = 90^\circ$$

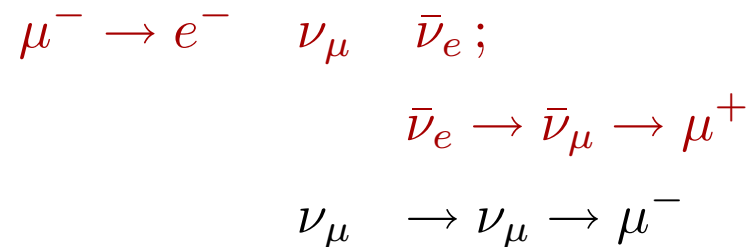
The challenge

We need to measure for the first time small oscillation probabilities: **need more intense and purer ν sources**

- **Superbeams** ν from K, π decay (off-axis)

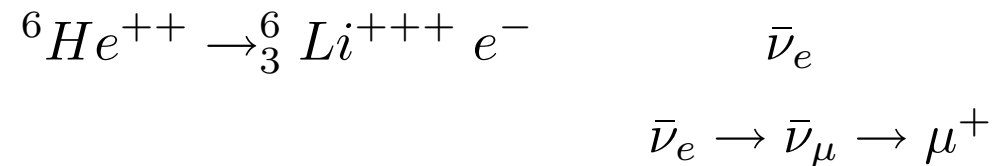


- **Neutrino factory** ν from muon decay



- β -beams from boosted heavy ions decays

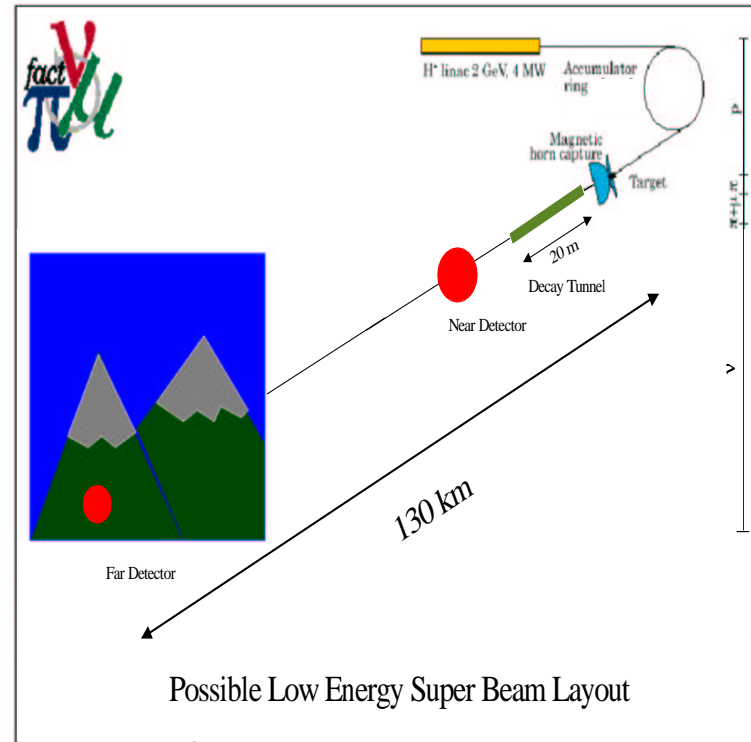
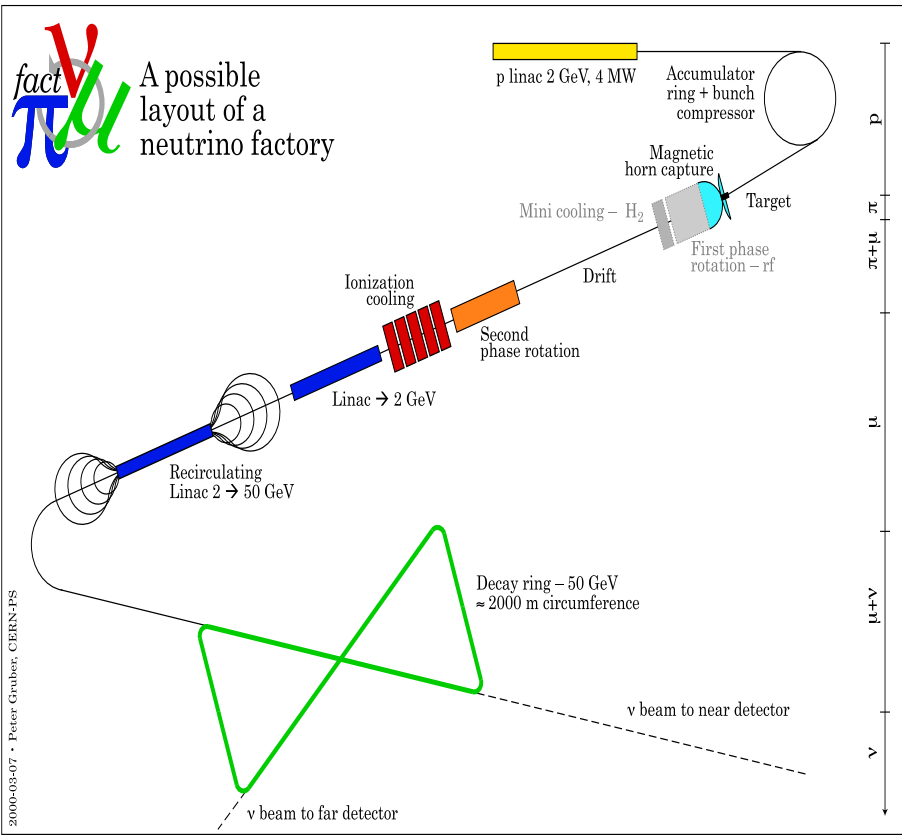
Zucchelli



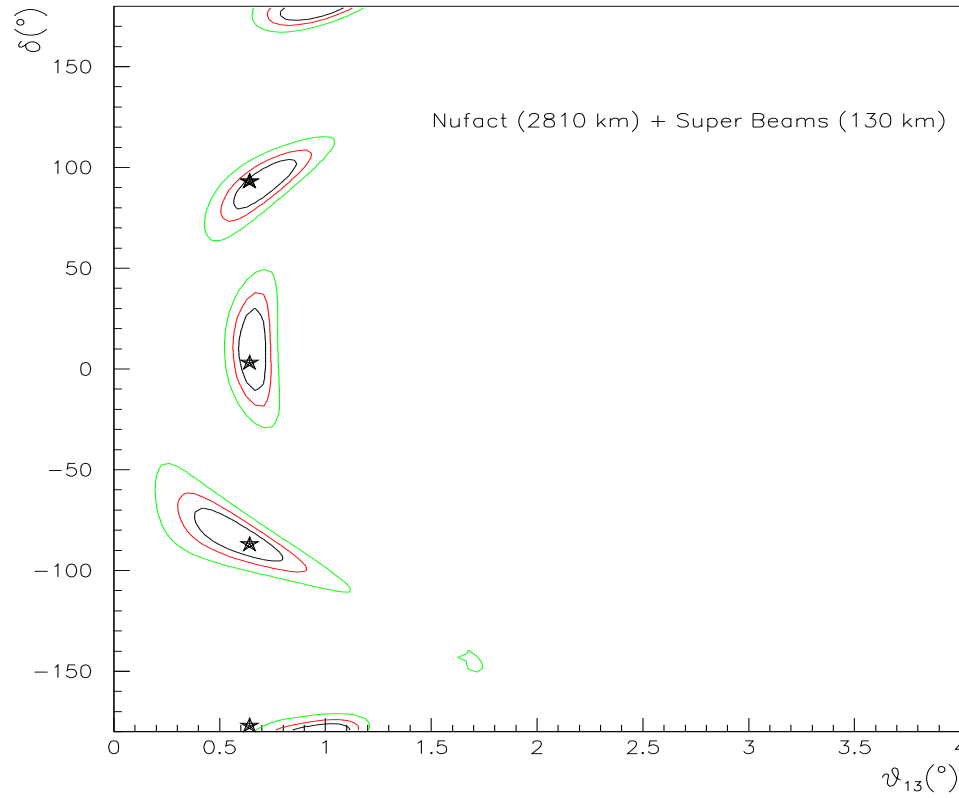
⇒ Radioactive beams for nuclear physics and neutrino physics Moriond '03 workshop

The synergies between these options are very large both on their physics reach and in the machine

The path to leptonic CP violation



The measurement of leptonic CP violation



Burguet-Castell, et al

4. Establish the Majorana nature of neutrinos and associated phases α_1, α_2
5. Determine the absolute ν mass scale \leftrightarrow new physics scale

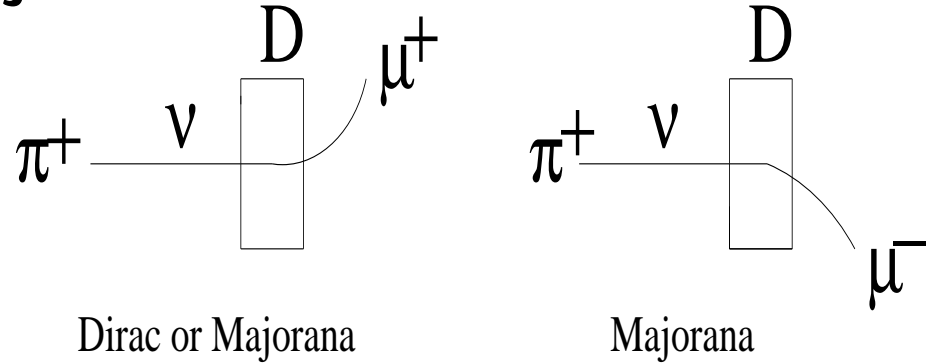


End-point of tritium β -decay

Rare \mathcal{L} violating decays: $0\nu\beta\beta$ decay

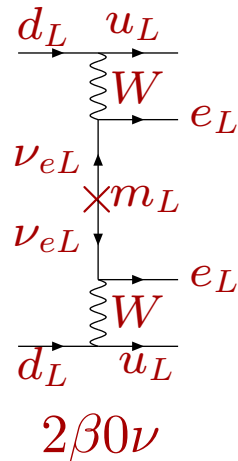
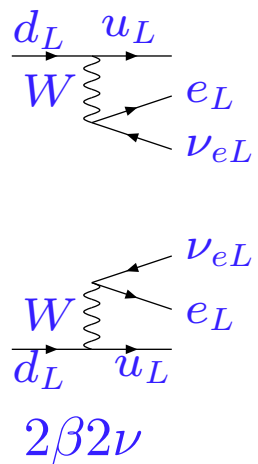
Dirac or Majorana ?

In principle there are very clear signatures:



Unfortunately these processes are suppressed by m_ν/E in amplitude: very rare !

Best hope through **neutrinoless double-beta decay**



$$T_{2\beta 2\nu} \sim 10^{19} - 10^{21} \text{ years}$$

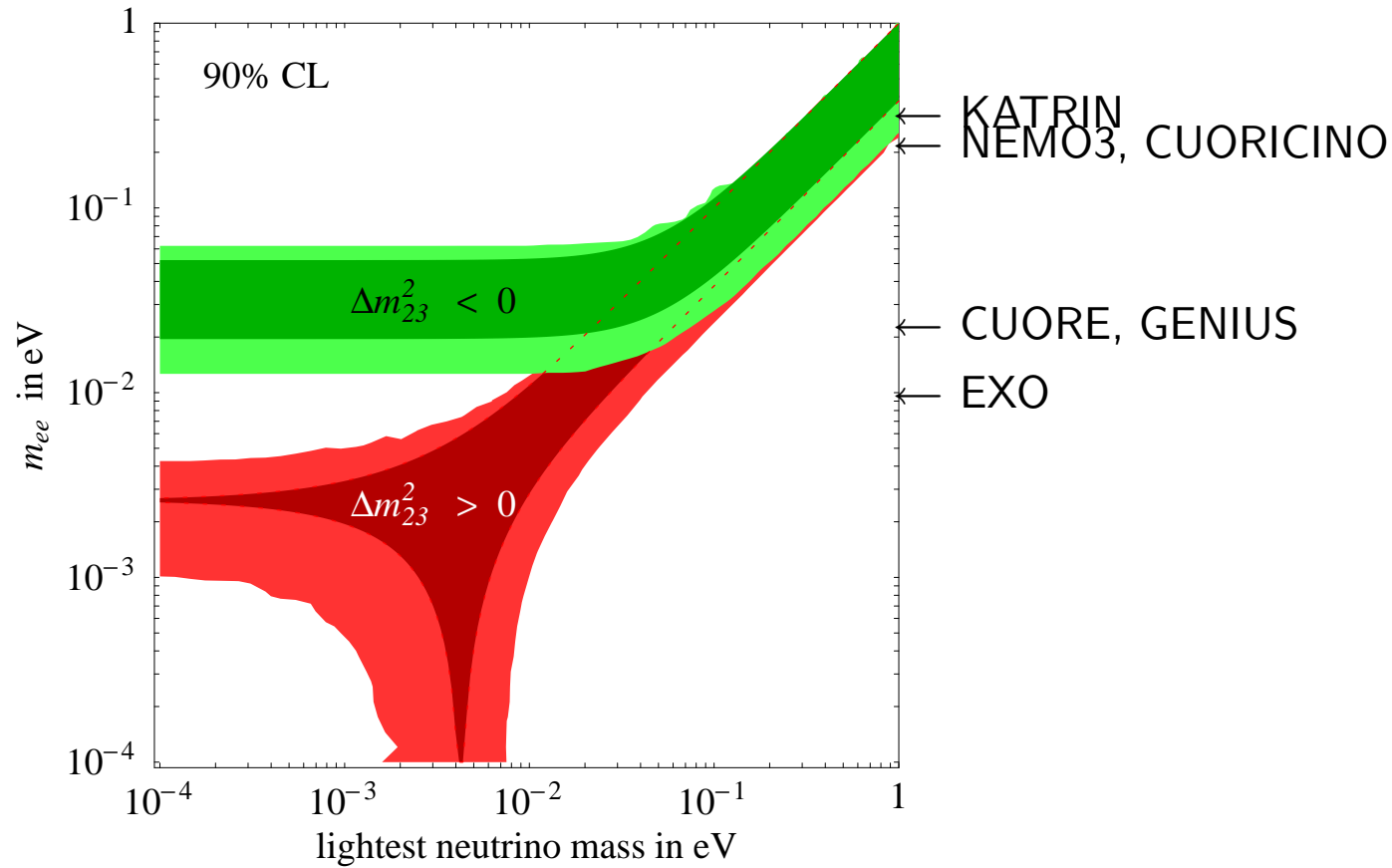
$$T_{2\beta 0\nu} \sim \left(\frac{m_\nu}{E}\right)^2 10^{-9} T_{2\beta 2\nu}$$

$$A(2\beta 0\nu) \sim m_{ee} \equiv \sum_i \left(V_{MNS}^{ei}\right)^2 m_i$$

$$|m_{ee}| < 0.35 \kappa \text{ eV} \quad \kappa = O(1)$$

Klapdor-Kleingrothaus, et al

Plethora of forthcoming experiments: NEMO3, CUORE, EXO, GENIUS...



Feruglio, Strumia, Visani

In the case of a positive signal: Majorana nature and maybe the mass scale, the hierarchy!

Conclusions

- An ingenious experimental effort is being devoted to prove the neutrino oscillation hypothesis beyond possible doubt:
 - The up-down asymmetry in the atmospheric ν_μ neutrino flux
 - The presence of ν_μ and/or ν_τ in the solar ν flux
 - The disappearance of japenese reactor neutrinos in their way to KamLAND
- ν masses almost certainly imply a new physics scale , which might be related to a GUT scale
- The determination of all the parameters in the neutrino mass matrices will be very valuable information to understand the dynamics of this new physics scale
- Even if neutrinos are no longer good candidates for dark matter, they are for visible matter: they can explain the observed baryon number in the Universe!

Only if there is violation of L and of CP in the lepton sector

- Testing this is a challenging task which will require more precise neutrino experiments and some luck...

