Prospects in Neutrino Physics

J. Bernabeu
U. Valencia, IFIC and CERN

Predicting the Future?

- “ In Physics it is very difficult to make predictions, especially if they refer to the Future”

  Victor Weisskopf

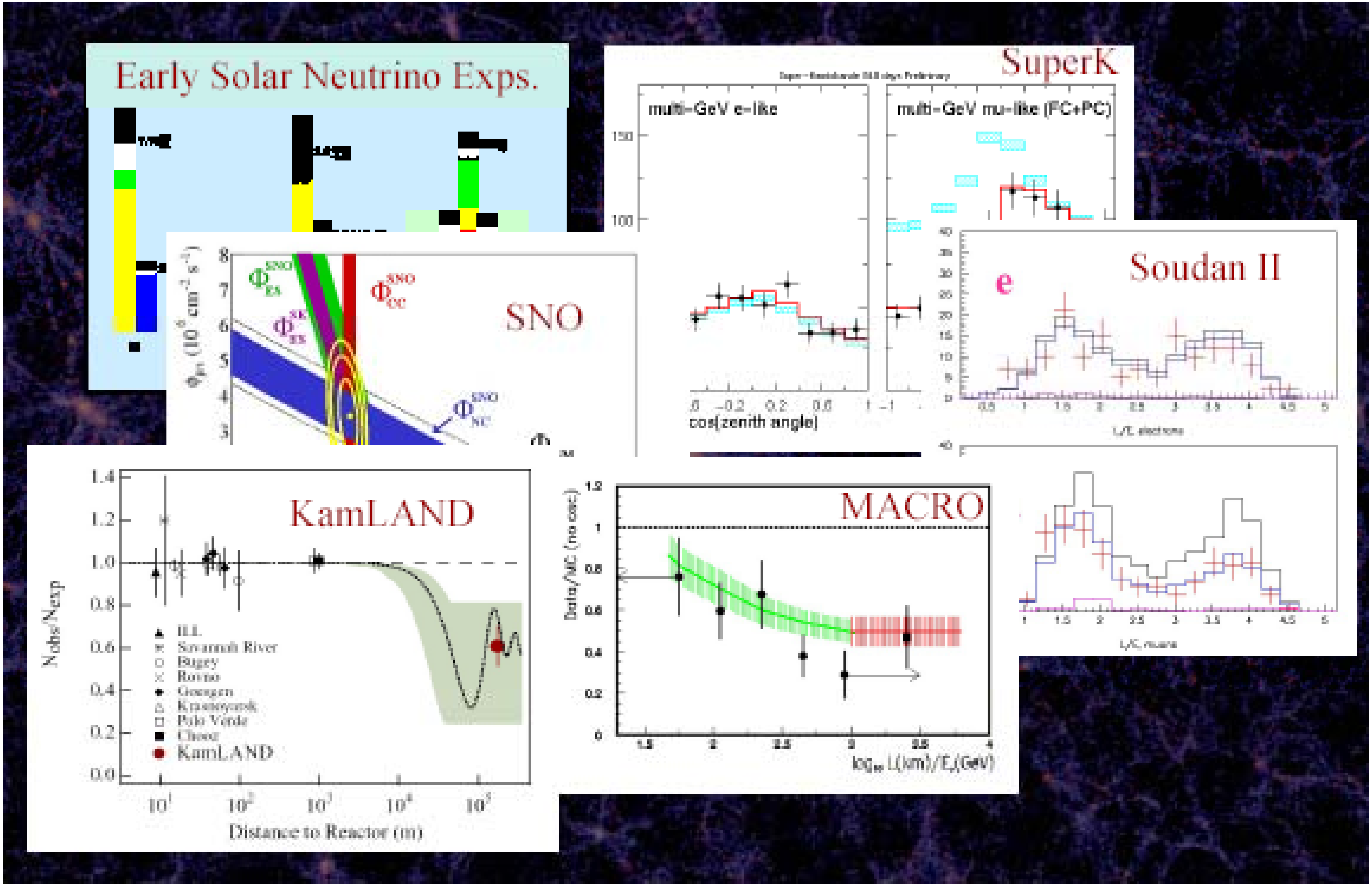
- The existence of a Road Map is neither a necessary nor a sufficient condition to assure the success of the enterprise in Scientific, Political or Sociological Adventures. The counter indication is for example the Political and Sociological Transition from Dictatorship to Democracy 30 years ago in Spain.

- Even so, with the present organization of Science Planning I will try to do my job.

Programme

- Experiments 1998 → 2007 in Neutrino Oscillations
- What is known, what is unknown
- Only three? : MiniBoone + Cosmology
- Solar and Atmospheric Sectors
- Second Generation Experiments for U(e3)
- Neutrino Mass Hierarchy from Atmospheric Neutrinos
- Absolute Mass from Cosmology and Beta Decay
- Majorana Neutrinos? Effective Mass from Double Beta Decay
- Third Generation Experiments: Dirac and Majorana CPV
- Outlook

Experiments 1998 - 2007



The Pontecorvo MNS Matrix

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

After diagonalization of the neutrino mass matrix,

→ **For Flavour oscillations**
U: 3 mixings, 1 phase

Even if they are Majorana

$$U_D = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

~Atmospheric
KEK
More LBL-beams

Appearance $\nu_\mu \rightarrow \nu_e$!
Reactor
Matter in Atmospheric…

~Solar
KAMLAND
Borexino

If Neutrinos are Majorana

- The mass eigenstates are selfconjugate up to a phase. The relative phases between two neutrinos become observable

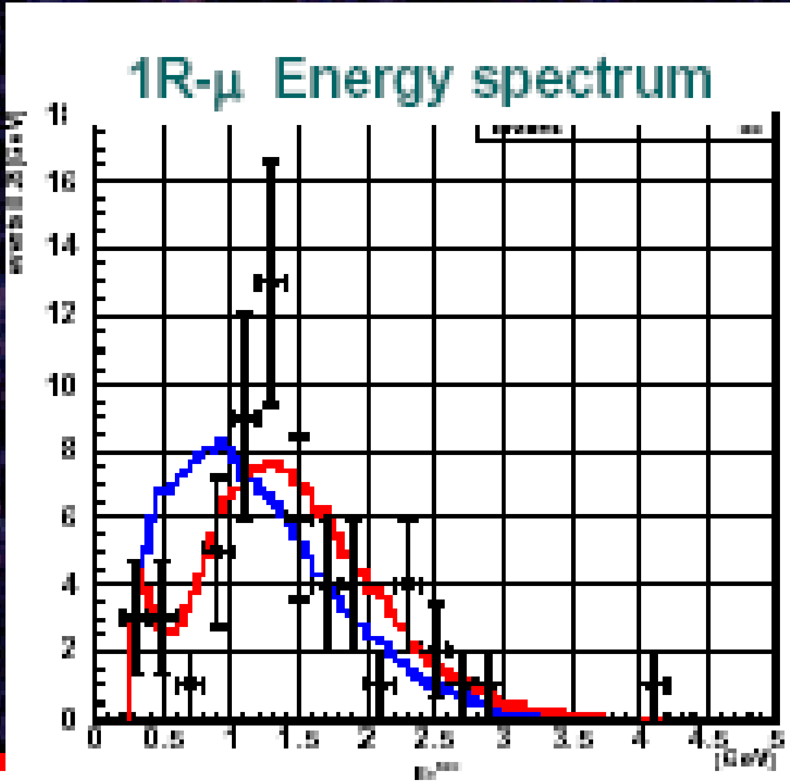
$$\begin{Bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{Bmatrix} = U \begin{Bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{Bmatrix} \longrightarrow \quad U = U_D \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\frac{\phi_1}{2}} & 0 \\ 0 & 0 & e^{-i\left(\frac{\phi_2}{2}+\delta\right)} \end{pmatrix}$$

- If these new phases have values of 0, π → the relative CP eigenvalues of the Majorana neutrinos are +, -, respectively.

- The Majorana character is only observable for processes ΔL=2 through the mass term that connects interacting neutrinos with antineutrinos:

$^{A}Z \rightarrow {}^{A}(Z+2) + 2e^-$, $\mu^- + {}^{A}Z \rightarrow e^+ + {}^{A}(Z-2)$, $\mu^- \rightarrow e^+ + 2e^-$(in 2nd. order)

Final K2K Statistics



	N_{sk}^{obs}	N_{sk}^{pred}
All	**112**	155.9
1 ring	**67**	99.0
μ-like	58	90.8
e-like	9	8.2
multi-ring	**45**	56.8

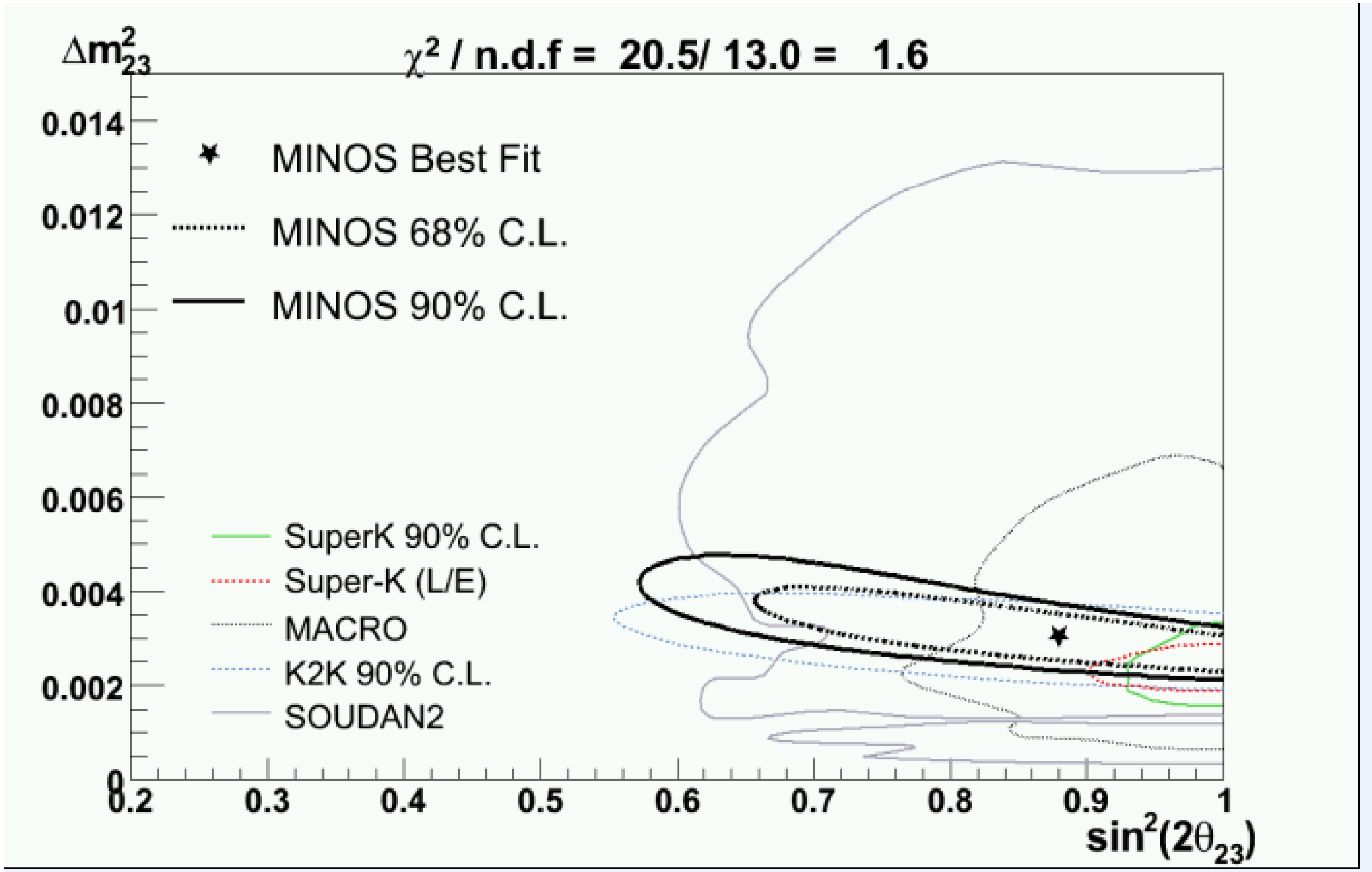
Oscillation – disappearance – two flavors analysis

$\sin^2 2\theta = 1.19 \pm 0.23$ $\Delta m^2 = (2.55 \pm 0.40) \times 10^{-3} eV^2$

$1.88 \times 10^{-3} \leq \Delta m^2 \leq 3.48 \times 10^{-3}\ eV^2$ (90%CL) for $\sin^2 2\theta = 1$

Results from MINOS

- From Fermilab to Sudan, ν_μ disappearance: L/E dependence



Energy resolution in the detector allows a better sensitivity in Δm^2_{23} : compatible with previous results with some tendency to higher values

What is known, what is unknown

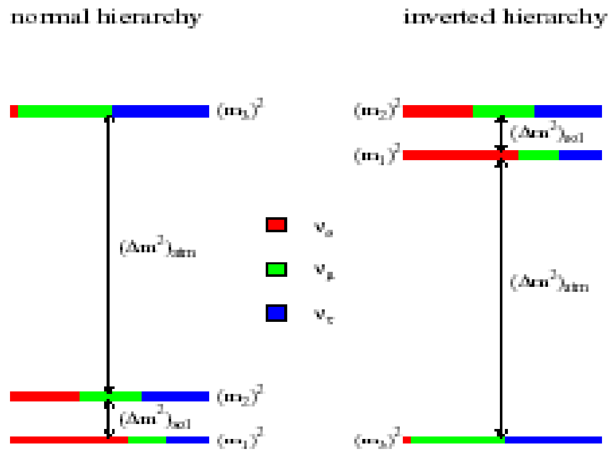
- **Neutrino flavour oscillations**

$$\begin{cases} \Delta m^2_{23} = 2.4\times10^{-3}\, eV^2 & \sin^2 2\theta_{23} = 1.00 \\ \Delta m^2_{12} = 8\times10^{-5}\, eV^2 & \sin^2 2\theta_{12} = 0.81 \\ \theta_{13} < 10^o & \delta \;\; ? \end{cases}$$

- **Absolute neutrino masses ?** → ^3H beta, Cosmology

- **Form of the mass spectrum**

  →Matter effect in neutrino propagation



- **Majorana neutrinos** ? → 0νββ: masses and phases

Three Generations of Experiments

- 0. Only three? → MiniBoone + Cosmology
- I. Solar Sector, Atmospheric Sector →

$\Delta m^2_{12}, \theta_{12}$ | $|\Delta m^2_{23}|, \theta_{23}$

Borexino | OPERA

- II. Connection between both Sectors →

θ_{13}, Sign (Δm^2_{23}) Double CHOOZ, T2K, NOVA, INO, …

Absolute Masses → Cosmology + Beta Decay

- III. CP-Violating Interference → $\delta, \ \Phi_{2,3}$

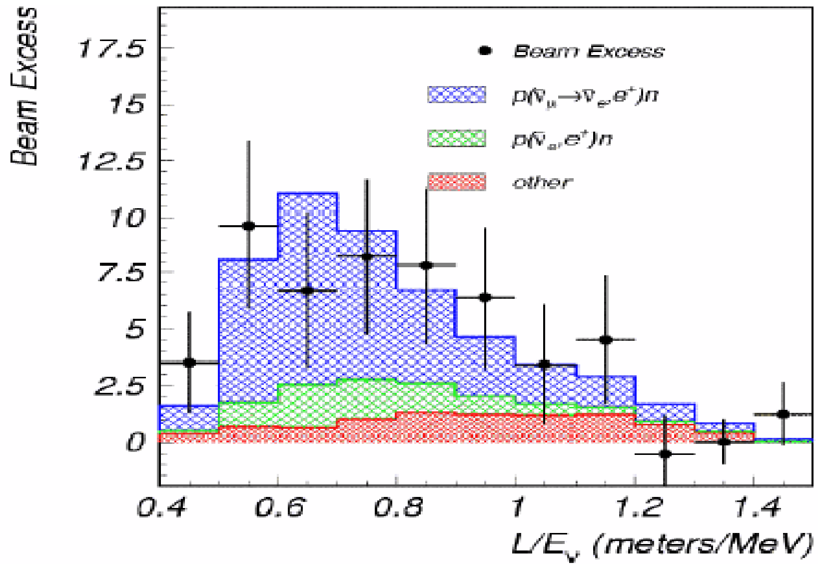
Super-Beams? Beta/EC Beams? Neutrino Factory?
Double Beta Decay: Effective Mass

Only three?

MiniBooNE was approved in 1998,
with the goal of addressing the LSND anomaly:

an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam,
87.9 ± 22.4 ± 6.0 (3.8σ)

which can be interpreted as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations:



Points -- LSND data
Signal (blue)
Backgrounds (red, green)

LSND Collab, PRD 64, 112007

LSND "Inclusion" Plot

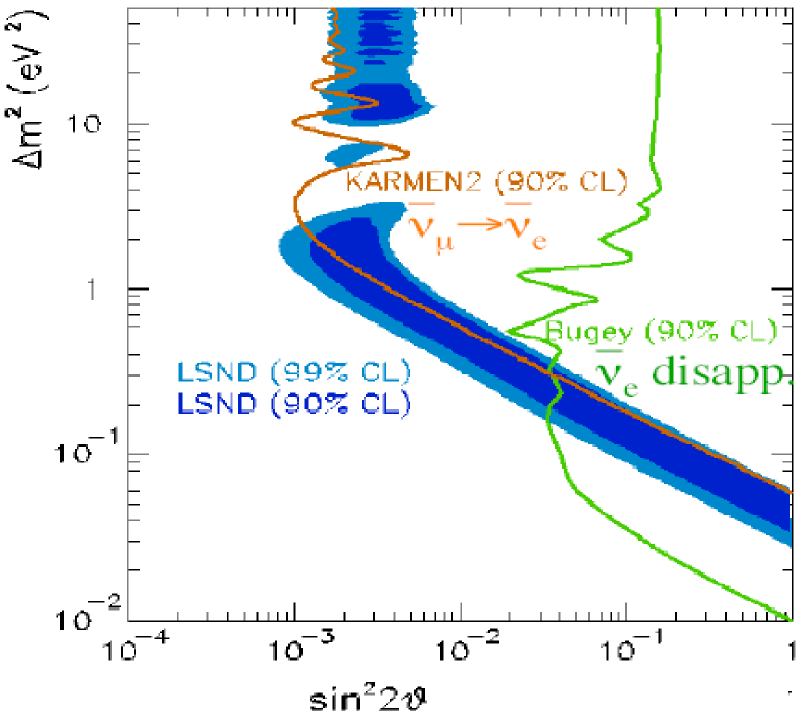
Within a $\nu_\mu \rightarrow \nu_e$ appearance model

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

mixing angle

squared mass difference

$\frac{\text{travel distance}}{\text{energy}}$ of the neutrinos



This model allows comparison to other experiments:

Karmen2

Bugey

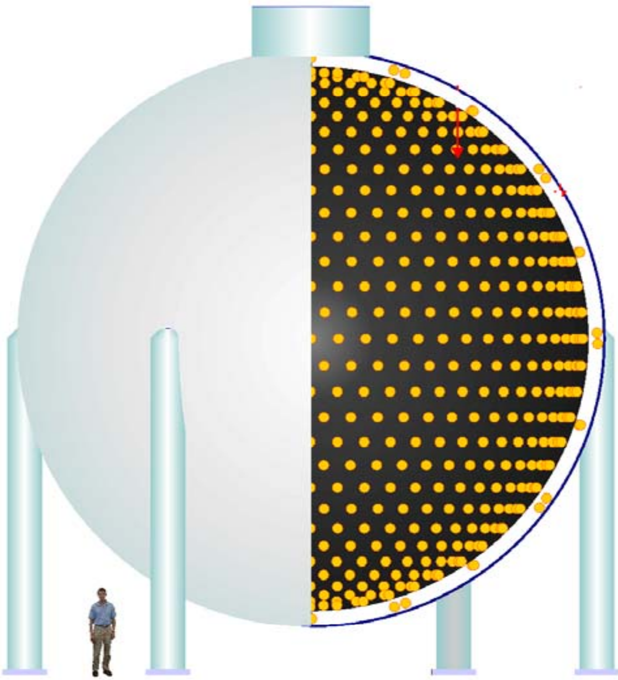
Joint analysis with Karmen2:
64% compatible

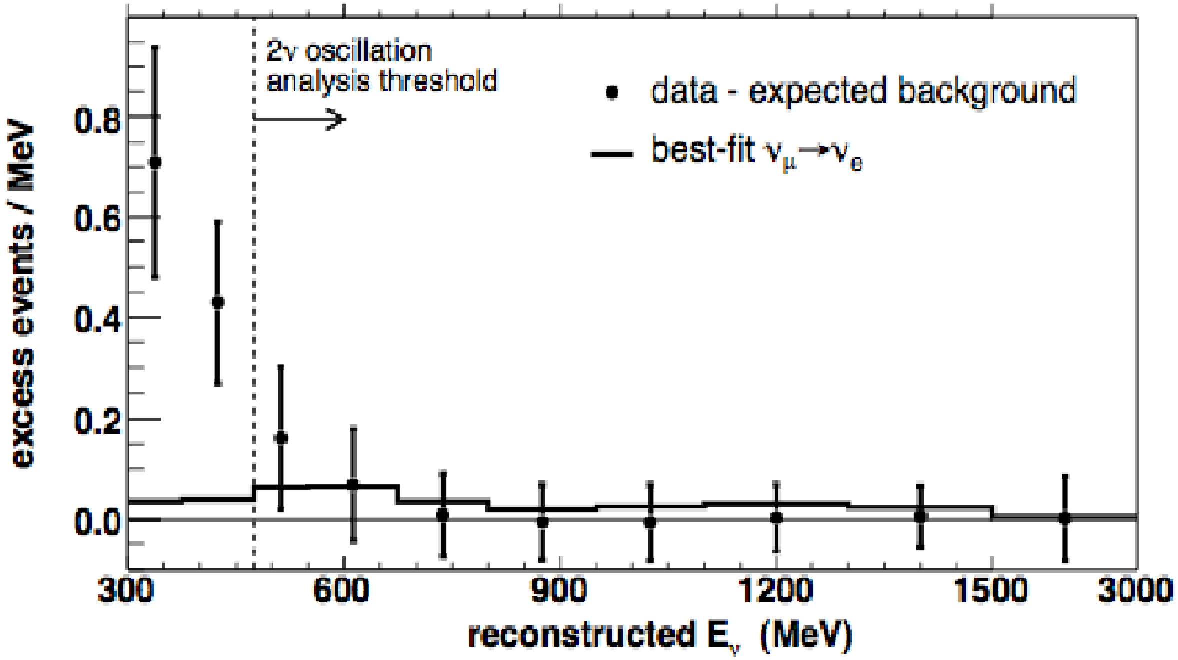
Church, et al., PRD 66, 013001

MiniBoone First Results

Within the energy range defined by this oscillation analysis, the event rate is consistent with background.

MiniBooNE Detector

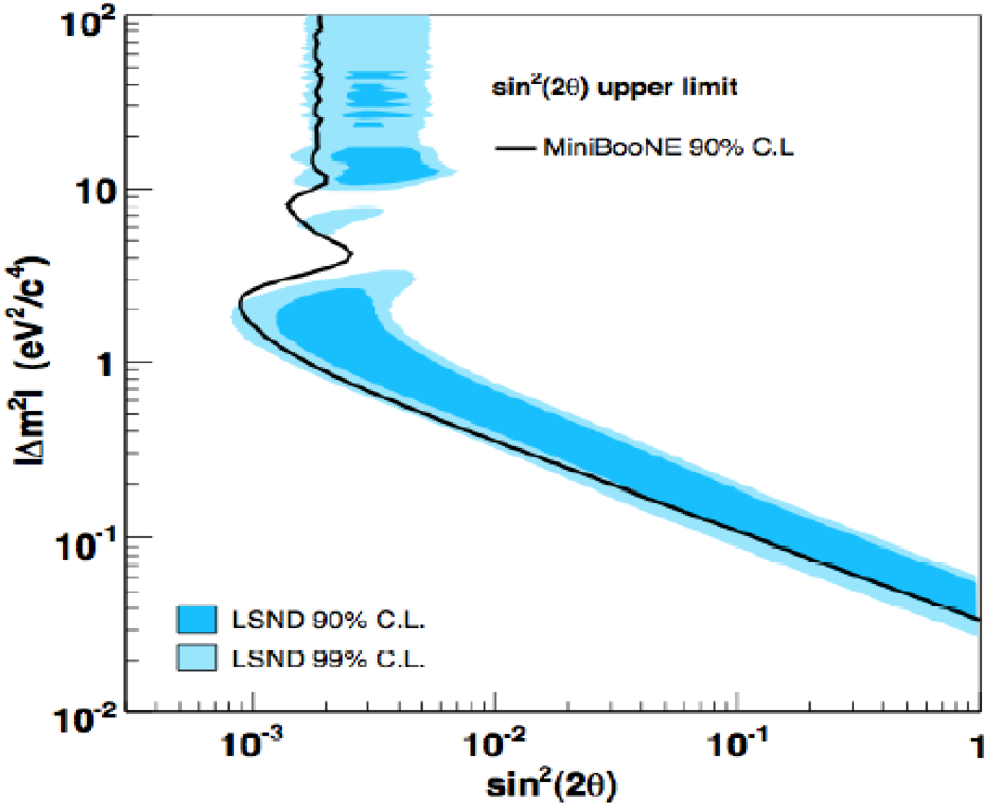




The observed low energy deviation is under investigation.

MiniBoone Exclusion Plot

The observed reconstructed energy distribution is inconsistent with a $\nu_\mu \to \nu_e$ appearance-only model



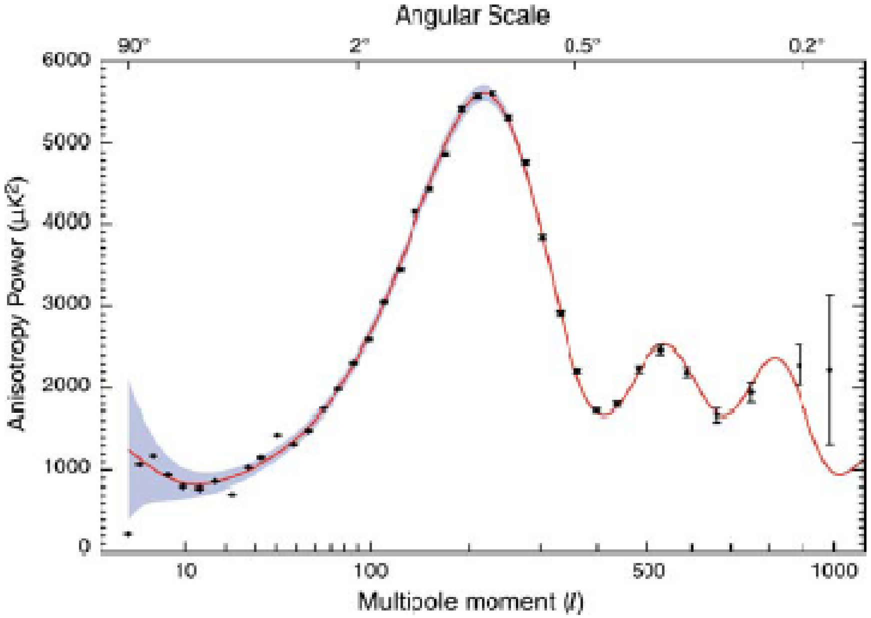
Therefore we set a limit on $\nu_\mu \to \nu_e$ appearance

PLANCK > 2008
Effective Number of Neutrinos

- New Constraints on any Physics BSM that contributes to the Energy Density of the Universe like Radiation, for example, Sterile Neutrinos

$$\rho_X \equiv \Delta N_\nu \rho_\nu = \frac{7}{8} \Delta N_\nu \rho_\gamma$$

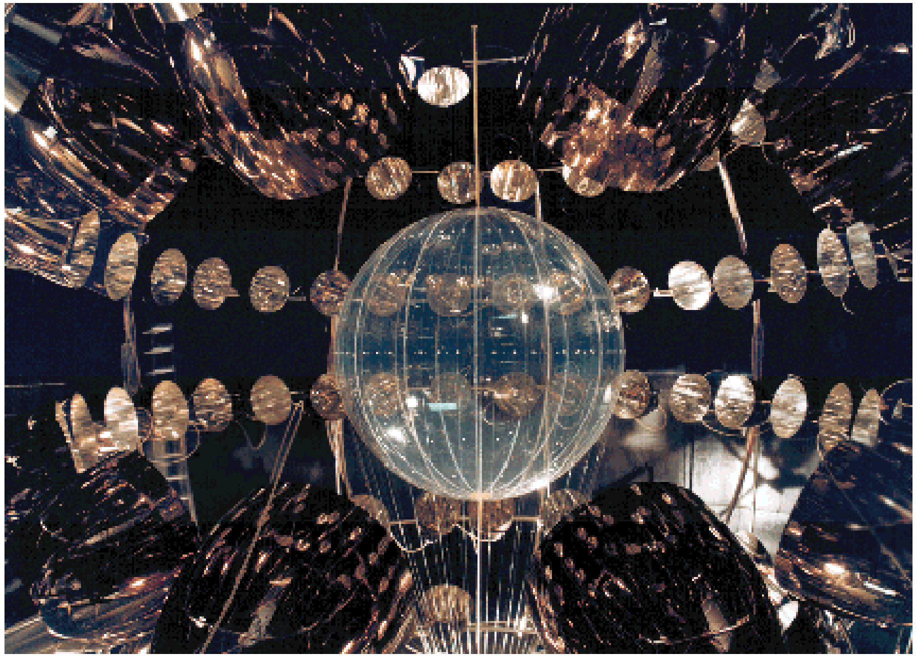
$\rho_X \neq 0$ changes the redshift of matter-radiation equality, affecting the CBR Power Spectrum. If $\rho_X > 0$, the matter-radiation equality is delayed and occurs closer to Recombination

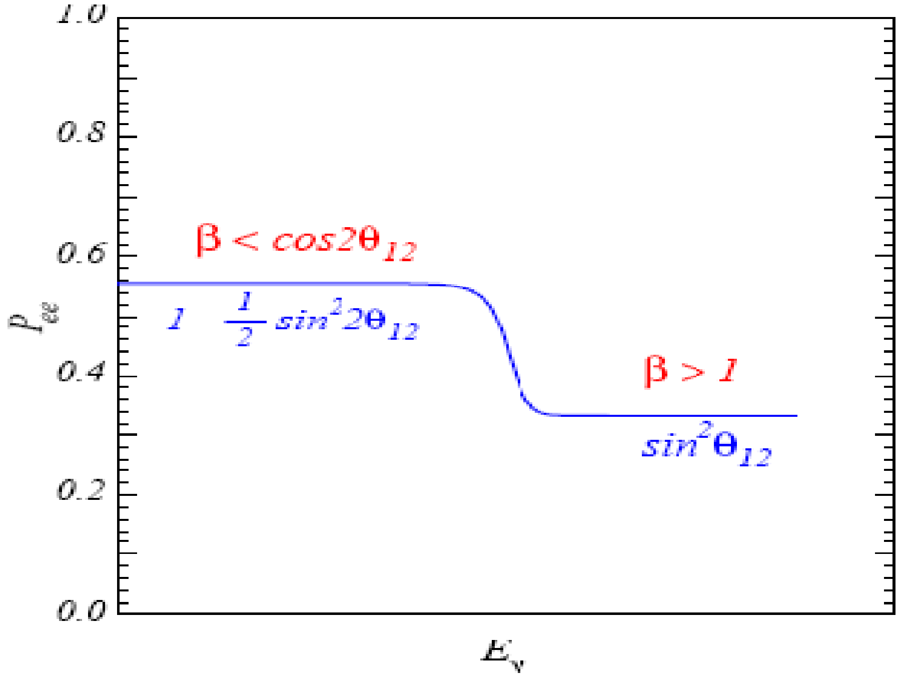


From WMAP → $\Delta N_\nu \leq 5$; PLANCK Sensitivity ~ 0.5

Constraining the Solar Sector

• **BOREXINO** is a new solar neutrino experiment at LNGS designed to detect low-energy solar neutrinos, in real time, using 300 tons of liquid scintillator in an unsegmented detector.





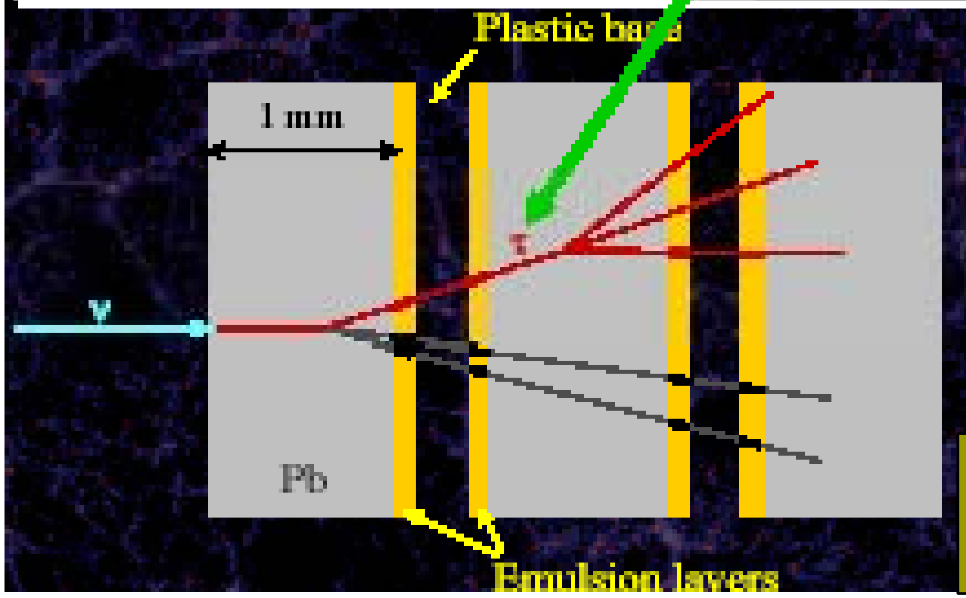
• The expected count rate is 50 events per day (SSM), due mostly to Be-7 solar neutrinos. This is the region of the transition energy between matter and vacuum oscillations: β is the ratio of the corresponding oscillation lengths.

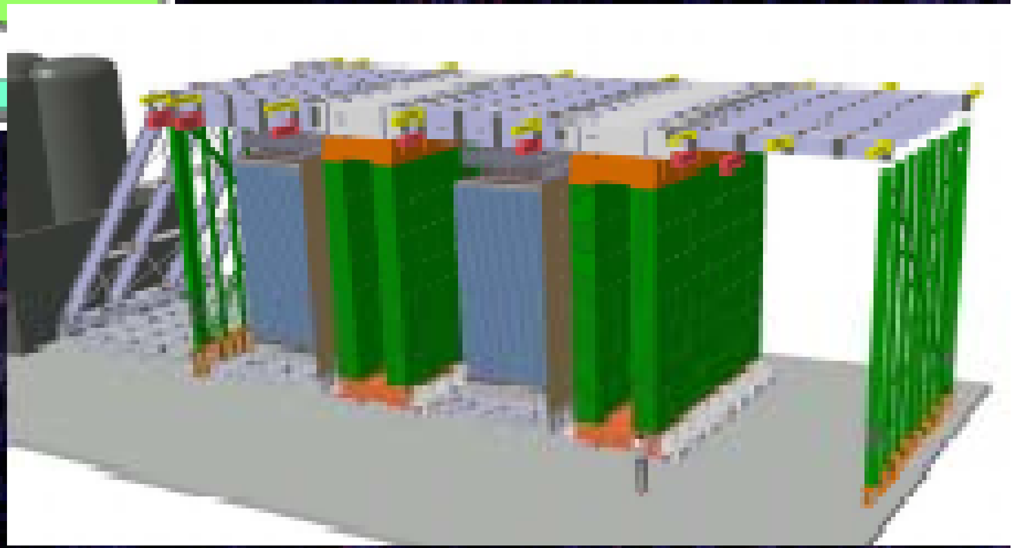
Atmospheric Sector- CNGS and OPERA

Clear signature of τ appearance

OPERA

5 yrs nominal running, best-fit SK
~12 signal events, ~1 background





First Appearance Experiment

Atmospheric Sector $\nu_\mu \rightarrow \nu_\tau$: OPERA

- May 2007: Cosmic Ray Test
- Schedule 2007: Neutrino Beam Exposure in September 2-3 weeks
  Real Neutrino Location will start this autumn

Expected Event Yield

Target Mass :1700 ton

Full mixing, 5 years run @ 4.5 x 10^{19} pot / year

ν_μ ν_e Interaction

ν_μ CC	23500
ν_μ NC	7075
$\bar{\nu}_\mu$ CC	494
ν_e CC	188
$\bar{\nu}_e$ CC	17

Clear ν_τ CC events

Δm^2	1.9×10^{-3} eV^2	2.4×10^{-3} eV^2	3.0×10^{-3} eV^2	B.G.
Final Design	8.0	12.8	19.9	0.8

Second Generation Experiments for U(e3)

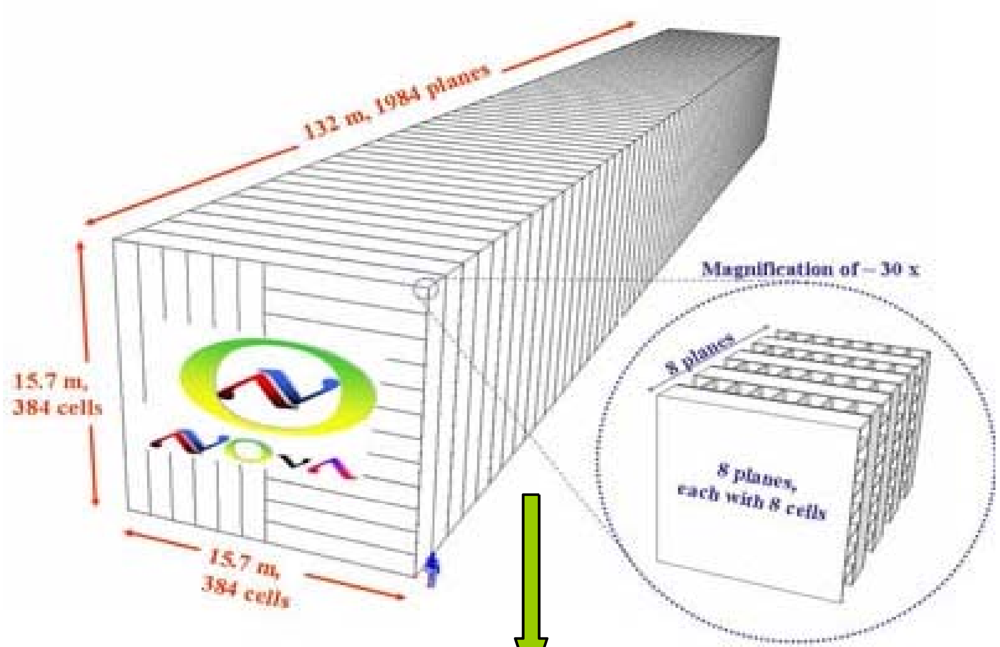
- Disappearance experiment from reactor $\overline{\nu}_e$: CHOOZ → Double CHOOZ will use two identical Detectors at 300 m and 1.05 Km.

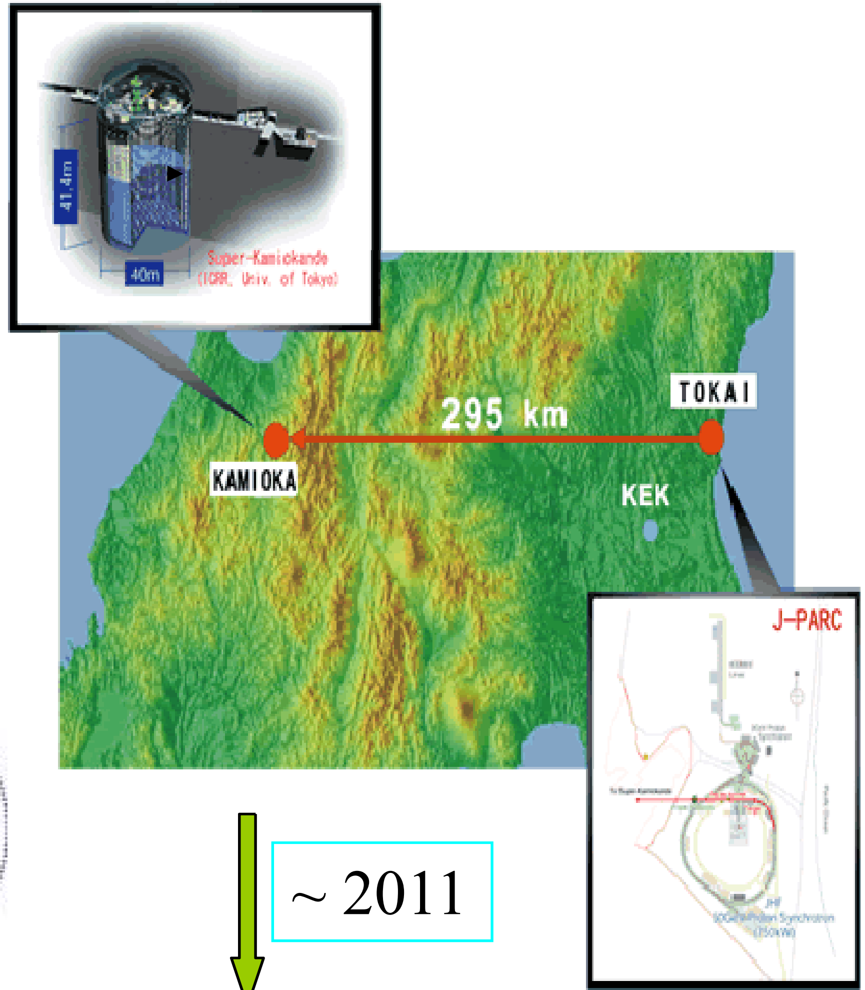
~ 2008

- The most stringent constraint on the third mixing angle comes from the CHOOZ reactor neutrino experiment with $\sin^2(2\theta_{13})<0.2$. Double Chooz will explore the range of $\sin^2(2\theta_{13})$ from 0.2 to 0.03-0.02, within three years of data taking.

Second Generation Experiments for U(e3)

- Appearance experiments for the suppressed transition $\nu_\mu \rightarrow \nu_e$: T2K, NOVA





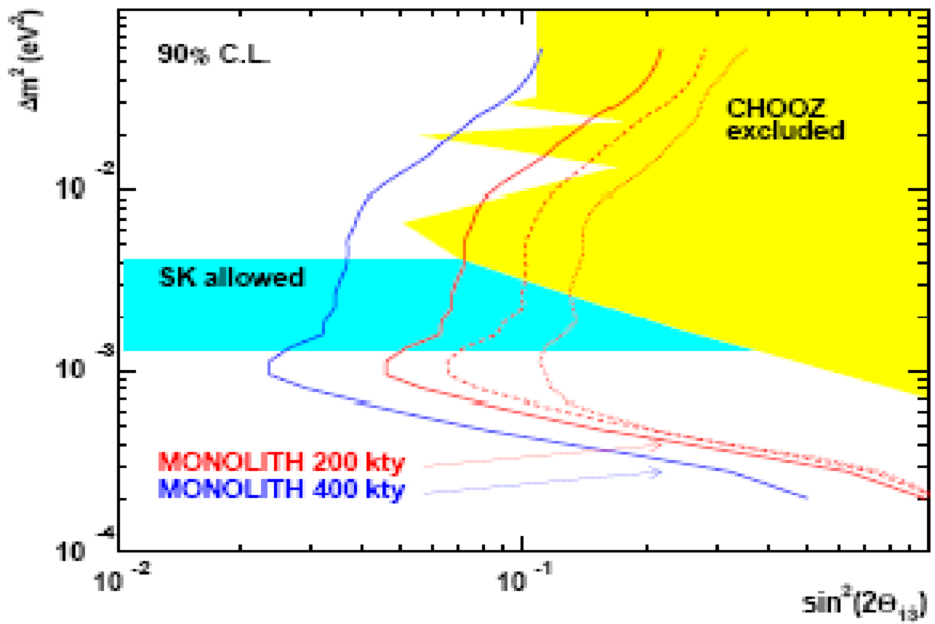
~ 2011

NOVA: off-axis neutrino beam from Fermilab to Soudan

T2K: from J-PARC to SK: 5 y $\sin^2 2\theta_{13} \sim 0.006$ if $\delta=0$ (?)

Neutrino Mass Hierarchy

- If U(e3)≠0 there are subdominant transitions of Atmospheric Neutrinos which can be amplified by Earth matter efects.
- If sign (Δm^2_{23}) >0 → Reduction of the rate of multi-GeV μ^- events: Resonant MSW for baselines L≥7000 Km.
- CP- and CPT- fake Asymmetry is unduced as a function of the zenith angle distribution: This needs a priori a detector with charge discrimination.

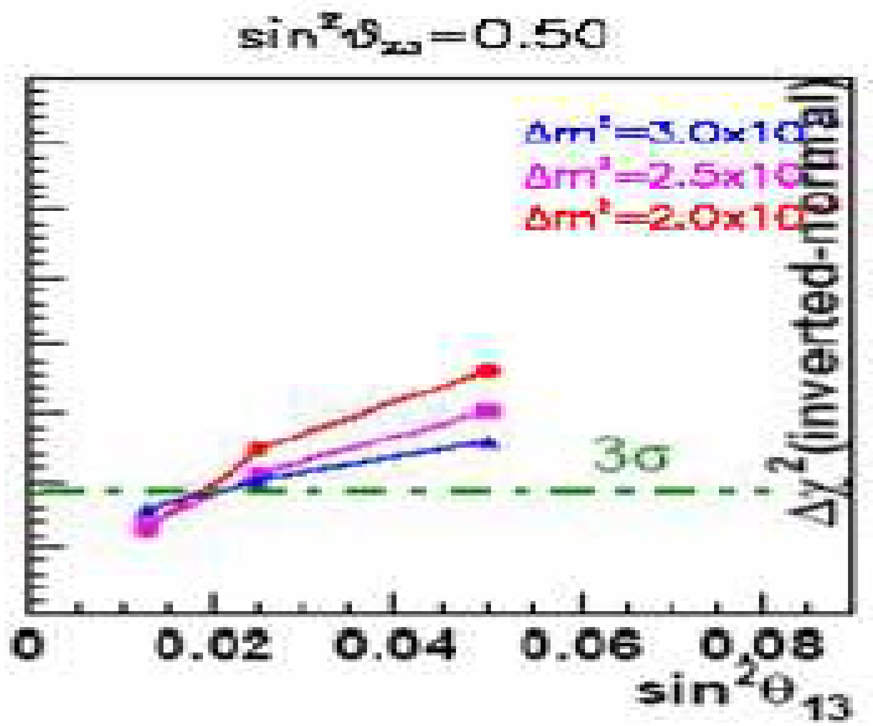


Sensitivity regions for which sign (Δm^2_{23}) can be determined, assuming that $\sin^2 2\theta_{13}$ is known with 30% accuracy (or previously unknown)

Neutrino Mass Hierarchy

- In Detectors without charge discrimination, the event- by-event distinction between Neutrino and Antineutrino events is not possible.
- However, due to the difference in cross sections, the multi-GeV samples of μ-like events will be smaller and those of e-like events will be larger if $\Delta m^2_{23} > 0$.
- Thus the ratio N(μ)/N(e) is sensitive to the form of the Neutrino Mass Spectrum.

Stastistical Significance for measuring sign (Δm^2_{23}) >0 for an exposure of 1.8 Mton yrs water Cherenkov detector



Absolute Mass from Cosmology

- Neutrinos left over from the early epochs of the evolution of the Universe have a number density of about 56 cm^{-3} for each of the six neutrino and antineutrino species and a black-body spectrum with temperature 1.947 K.
- The neutrino contribution to the matter density of the Universe is proportional to **$m_C = \Sigma_i m_i$**
- From the measurements of the two Δm^2, we may distinguish:
  1. Direct Hierarchy: $m_{lightest} = m_1 \rightarrow m_C \sim m_3 \sim 6.7 \times 10^{-2}$ eV
  2. Inverted Hierarchy: $m_{lightest} = m_3 \rightarrow m_C \sim m_1 + m_2 \sim 2m_1 \sim 9.8 \times 10^{-2}$ eV
  3. Quasi-Denegerate: $m_1 \sim m_2 \sim m_3 = m_0$, $m_0 \gg 4.9 \times 10^{-2}$eV $\rightarrow m_C \geq 0.3$ eV
- Present determinations of m_C from the Large Scale Structure of the Universe and the CMB missions give $m_C \leq (0.4\text{-}1.0)$ eV.
- Future Sensitivity of PLANCK is $m_C \sim 0.3$ eV. Combined with the Galaxy Survey SDSS + the weak Gravitational Lensing of Radiation from Background Galaxies, the Sensitivity can reach the value

$m_C \sim 0.1$ eV

Direct Measurement of Mass: Beta Decay

- The shape of the electron Spectrum in ^3H Beta Decay, near the kinematical end point, is sensitive to Neutrino Mass.
- For Energy Resolution $\Delta E >> m_i$, the Effective Mass which is measured is

$$m_\beta = \left(\sum_i m_i^2 |U_{ei}|^2\right)^{1/2}$$

- A priori it depends on U_{e3}, but…
  1. Direct Hierarchy: $m_\beta \sim (m_2^2 s_{12}^2 + m_3^2 s_{13}^2)^{\frac{1}{2}} \leq 10^{-2}$ eV
  2. Inverted Hierarchy: $m_\beta \sim m_{1,2} (|U_{e1}|^2 + |U_{e2}|^2)^{1/2} \sim m_{1,2} \sim 5 \times 10^{-2}$eV
  3. Quasi-Degenerate: $m_1 \sim m_2 \sim m_3 = m_0 \rightarrow m_\beta \sim m_0 >> 5 \times 10^{-2}$ eV
- Present experimental limit (Mainz, Troitzk): $m_\beta < 2.3$ eV.
- KATRIN will reach a sensitivity (~ 2010) $m_\beta \sim 0.2$ eV.
- Then: - If KATRIN observes distortion → Quasi-Degenerate

  - If KATRIN does not → Direct or Inverted

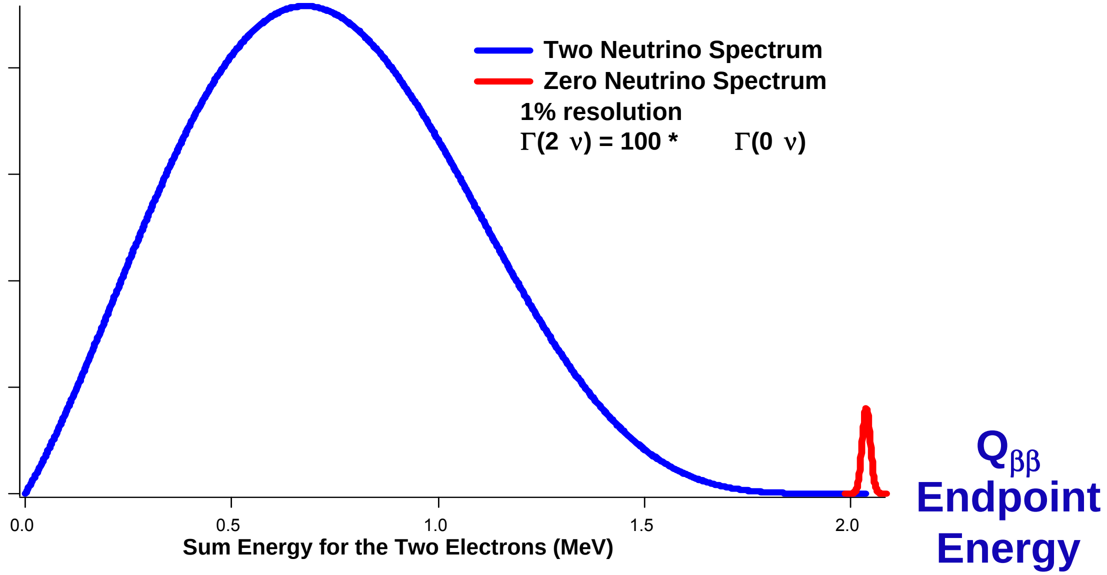
  - If a new Experiment becomes sensitive to $m_\beta \sim 5 \times 10^{-2}$eV, it will discriminate between Inverted (if signal) and Direct (no signal).

Neutrinoless Double Beta Decay

- Previous Mass measurements do not distinguish whether neutrinos are Dirac or Majorana particles.
- The existence of Neutrinoless Double Beta Decay is only possible if neutrinos are Majorana, violating Global Lepton Number in two units through their mass terms.
- For $^{A}Z \rightarrow {}^{A}(Z+2) + 2e^{-}$ the half-life is inversely proportional to the modulus square of

$$m_{\beta\beta} = \sum_i m_i U_{ei}{}^2 = m_1 c_{13}{}^2 c_{12}{}^2 + m_2 c_{13}{}^2 s_{12}{}^2 e^{-i\phi_2} + m_3 s_{13}{}^2 e^{-i\phi_3}$$

- It is sensitive to Mixings and CP Majorana phases.
- To extract $|m_{\beta\beta}|$ from the Experiment, one would need an accurate knowledge of nuclear matrix elements, which is not available at present.

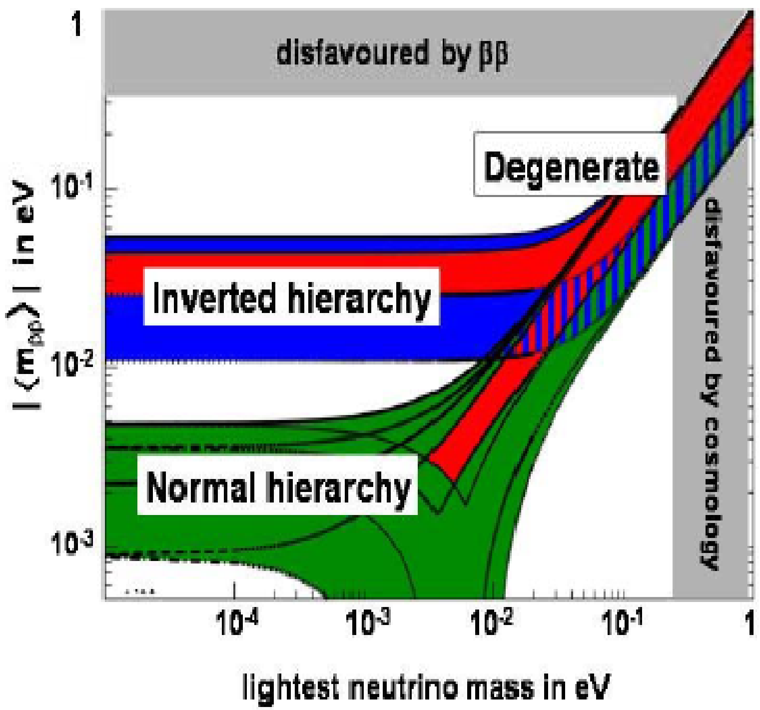


Neutrinoless Double Beta Decay

- Direct Hierarchy: $m_{\beta\beta}$ depends on $(\Phi_2-\Phi_3)$ for the two heaviest Majorana Neutrinos. Typical values are few x 10^{-3} eV and complete cancellation is possible. If $s_{13}^{\ 2} = 0.03 \rightarrow |m_{\beta\beta}| \leq 4 \times 10^{-3}$ eV.

- Inverted Hierarchy: $$\left|m_{\beta\beta}\right| = m_{1,2} c_{13}^2 (1 - \sin^2 2\theta_{12} \sin^2 \frac{\phi_2}{2})^{1/2}$$

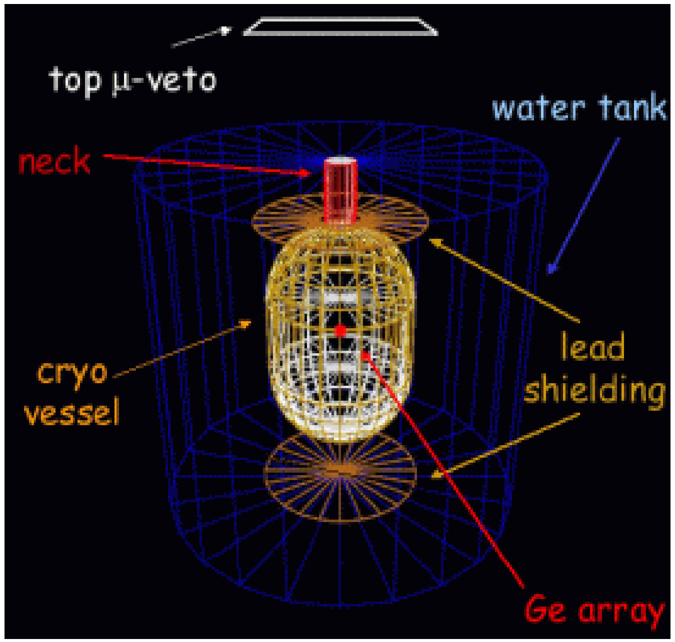
  which again depends on the CP Majorana phase Φ_2 but independent of s_{13}. A significant lower limit is 0.02 eV ($\Phi_2 \sim \pi$) and the maximum is 0.055 eV ($\Phi_2 \sim 0$).

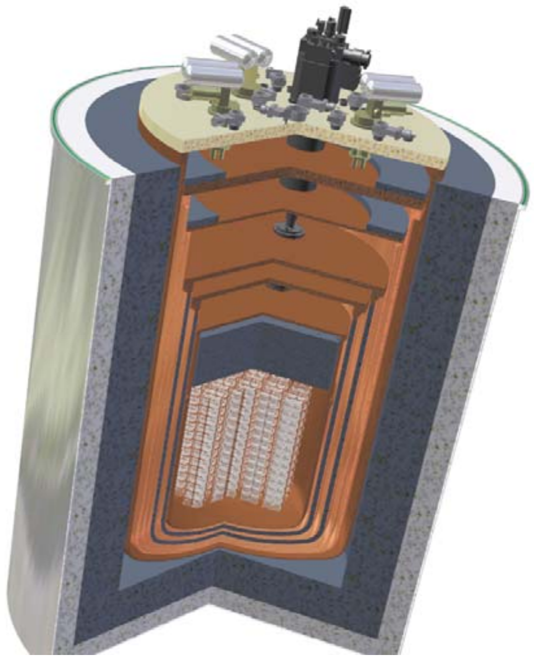


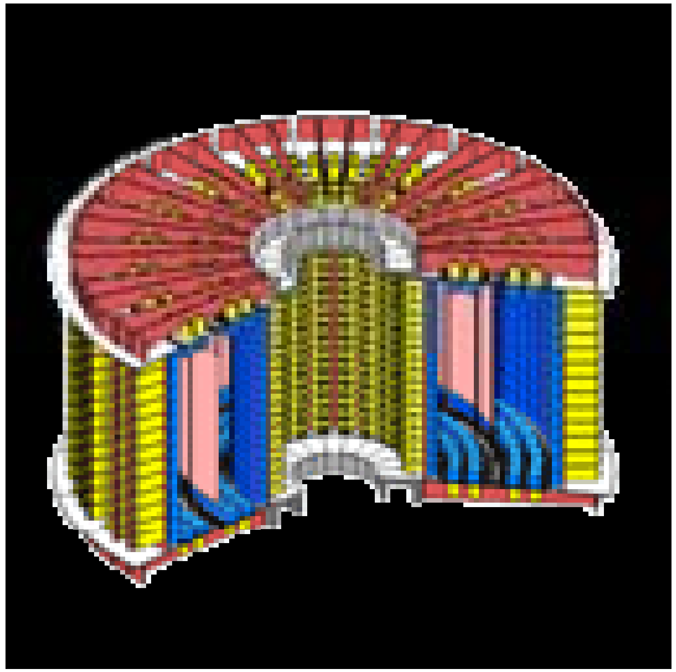
- Quasi-Degenerate: $m_1 \sim m_2 \sim m_3 = m_0 \geq 0.1$ eV, independent of the two Δm^2. A nontrivial lower limit is $|m_{\beta\beta}| \geq 0.08$ eV

Double Beta Decay Experiments

- Present best limits came from Heidelberg-Moscow (LNGS) and IGEX (Canfranc) ^{76}Ge Collaborations: $|m_{\beta\beta}|$< 0.4-0.9 eV.
- Running Experiments are CUORICINO (^{130}Te bolometers) and NEMO-3 (^{100} Mo and ^{82} Se foil sandwiched by Tracking). Sensitivities around 0.5 eV .
- European next-stage Detectors are GERDA (18 → 40 → 500 Kg of ^{76}Ge), CUORE (up to 740 Kg) and Super-NEMO (100 Kg of ^{150}Nd or ^{82} Se). Sensitivities will reach the level of 0.05-0.2 eV entering into the region of the inverted Mass Hierarchy.
- This endeavour will start between 2010 and 2012.







Third Generation Experiments: CP Violation

- After atmospheric and solar discoveries and accelerator and reactor measurements → θ_{13} , δ
- CP violation accessible in suppressed appearance experiments

- ***Appearance probability***:

$$P(\nu_e \to \nu_\mu) \approx \underbrace{s_{23}^2 \sin^2 2\theta_{13} \sin^2(\frac{\Delta m_{13}^2 L}{4E})}_{\text{Atmospheric}} +$$

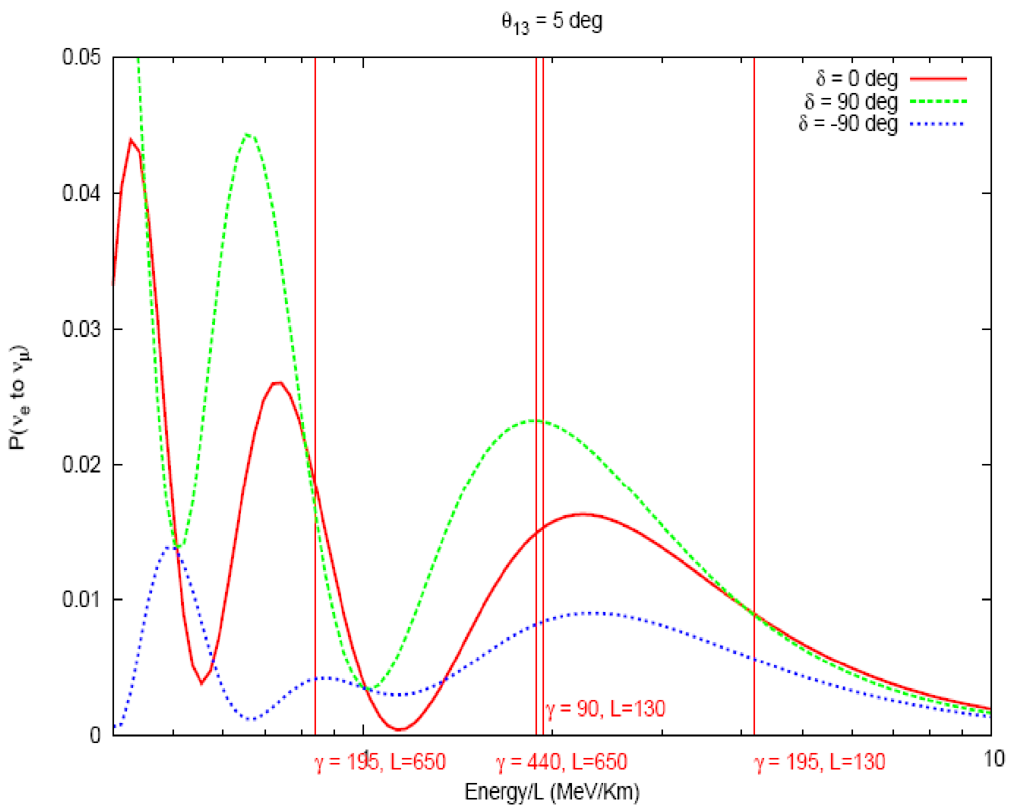
$$\underbrace{c_{23}^2 \sin^2 2\theta_{12} \sin^2(\frac{\Delta m_{12}^2 L}{4E})}_{\text{Solar}} +$$

$$\underbrace{\tilde{J} \cos(\delta - \frac{\Delta m_{13}^2 L}{4E}) \frac{\Delta m_{12}^2 L}{4E} \sin(\frac{\Delta m_{13}^2 L}{4E})}_{\text{Interference}}$$

- $|U_{e3}|$ gives the strength of $P(\nu_e \to \nu_\mu)$
  - δ gives the interference pattern: CP odd term is odd in E/L
  - This result is a consequence of a theorem under the assumptions of CPT invariance and absence of absorptive parts

Third Generation Experiments: CP Violation

- European Strategy Plan demands for ~ 2010 a CDR with the alternatives: SuperBeams, Beta/EC Beams, Neutrino Factory.
- **SuperBeam**: no pure Flavour, uncertain continuous Spectrum.
- **Beta Beam**: pure Flavour, known continuous Spectrum.
- **EC Beam**: pure Flavour, known single Monochromatic Beam.
- **Neutrino Factory**: pure Flavour iff detector with charge discrimination, known continuous Spectrum.

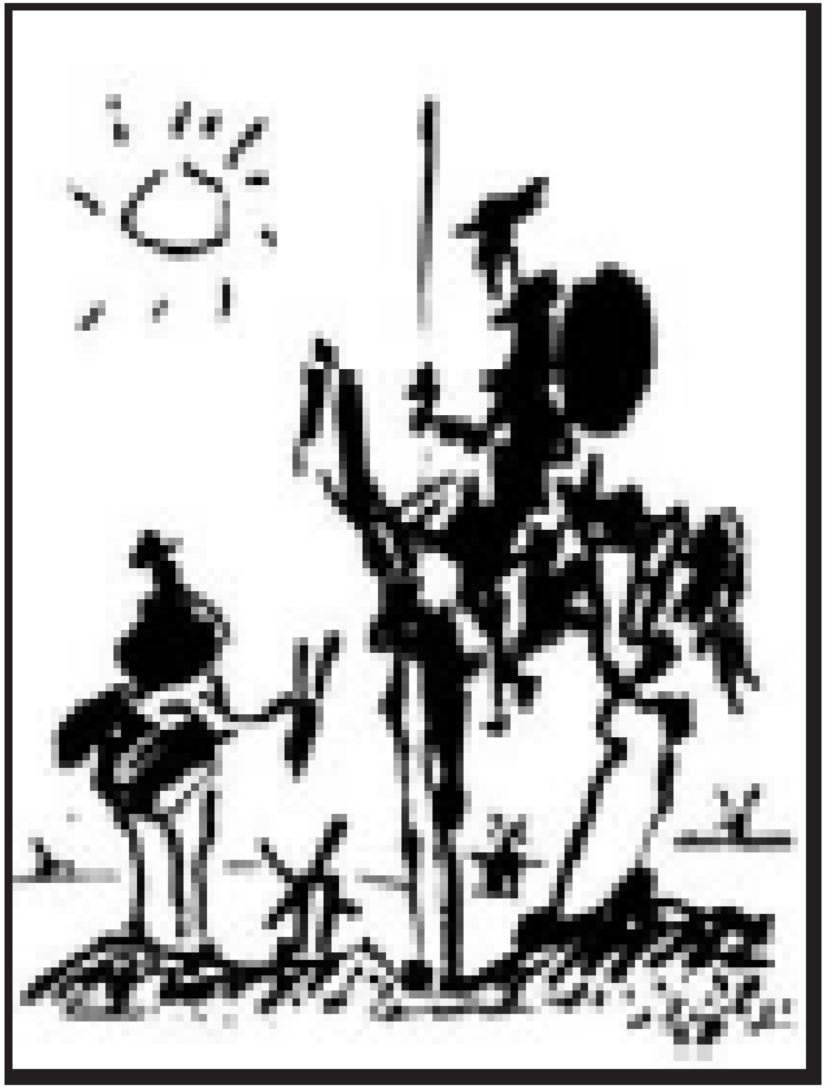


• ***CPV can be observed either by an Asymmetry between Neutrinos and Antineutrinos or by Energy Dependence (CP phase as a phase shift) in the Neutrino channel, or both.***

Outlook

ASPERA

- The result of the synergy of Neutrino Oscillation Physics with LHC- Physics (SPS upgrade) and, in the case of Beta/EC Beams, with Nuclear Physics (EURISOL) for the Facility at CERN, could be completed with the synergy with Astroparticle Physics for a Multipurpose Detector, common to neutrino oscillation studies with terrestrial beams, Atmospheric Neutrinos (neutrino mass hierarchy), supernova neutrinos and Proton decay!!!



MUCHAS GRACIAS!