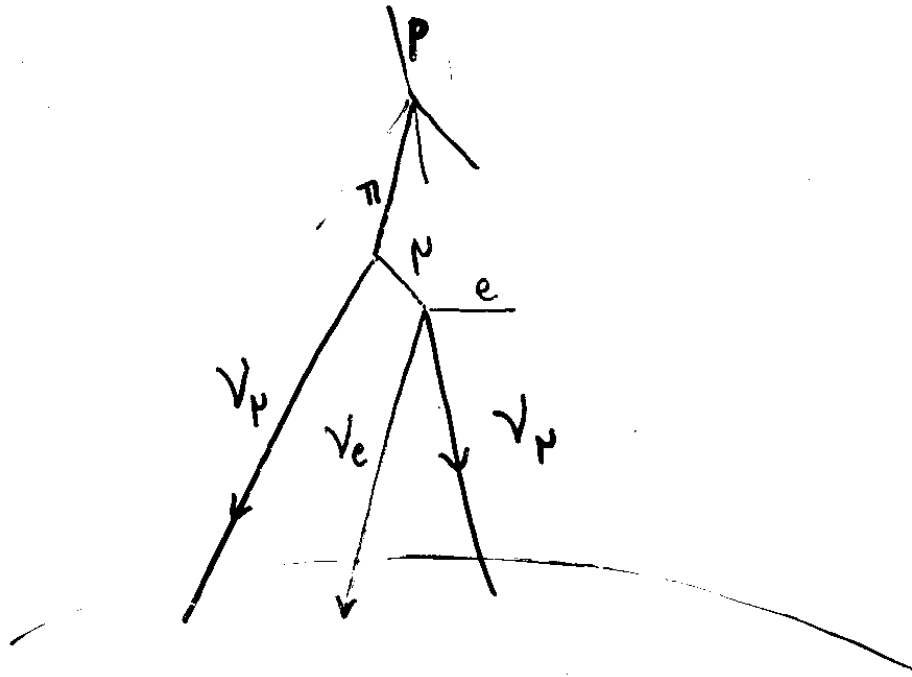


J. BOUCHEZ  
APC  
CEA/DAPNIA

ATMOSPHERIC  $\nu$ 's

③  
ISAPP 2003  
Madonna di  
Campiglio



$$v_{\mu}/v_e \geq 2$$

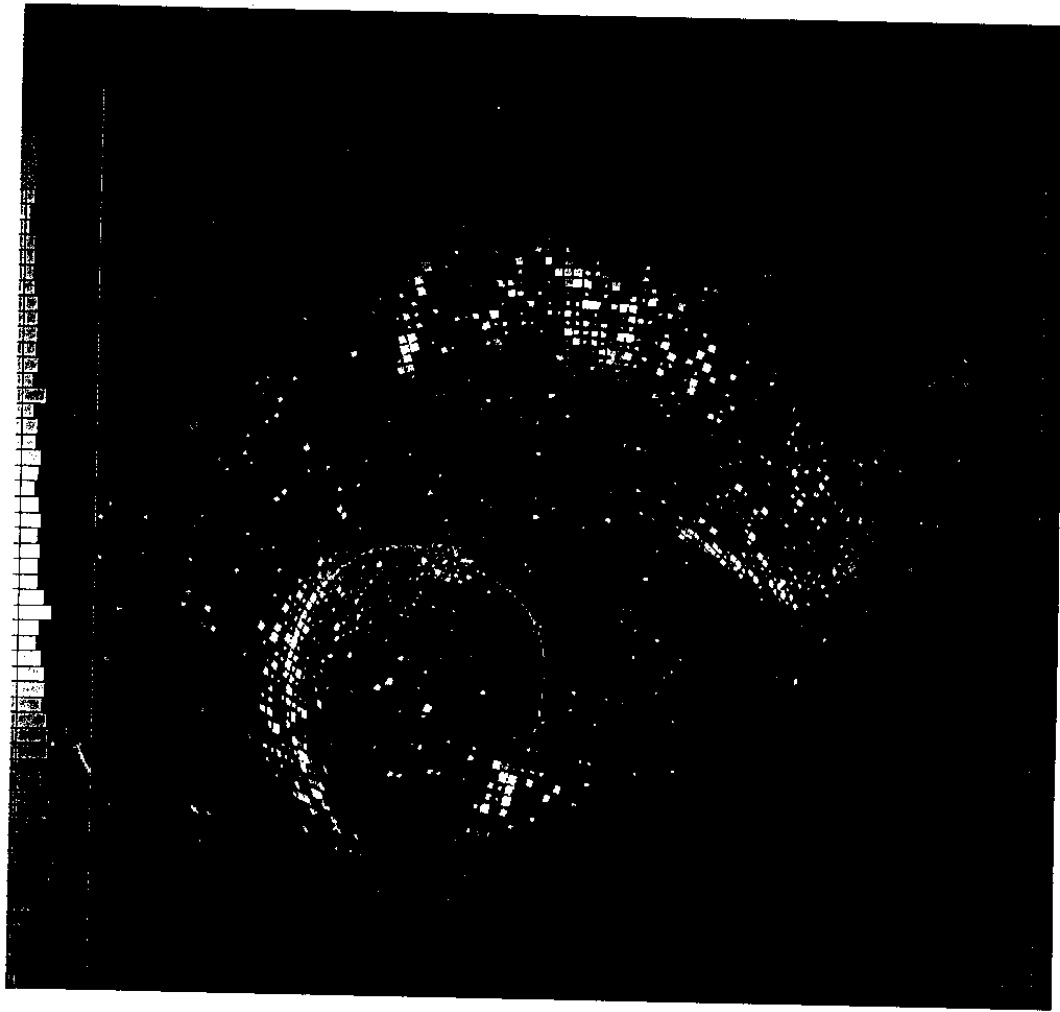
Observation (SK)  $v_{\mu}/v_e \sim 1$

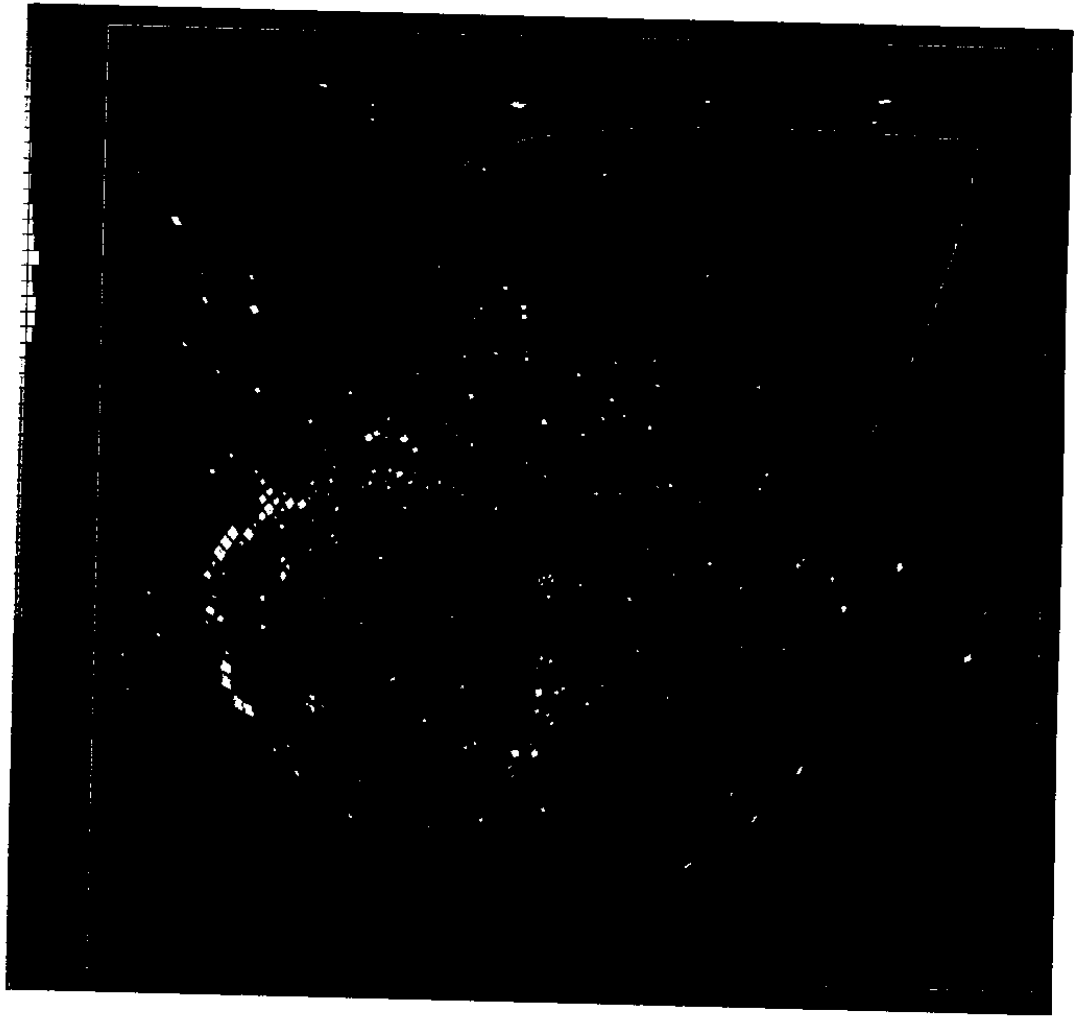
"Atmospheric anomaly"

The most precise results come from  
Super Kamioka

(mass of 50 kT, 22.5 kT fiducial)

- $e/\mu$  separation based on ring topology
  - $\mu$  = sharp edge
  - $e$  = fuzzy ring
- Only simple topologies (1 ring event) used in analyses
- Energy measured for contained  $e\nu$ 's  
(hadronic energy lost)
- $L/E$  badly determined





## Event Summary (848.3 d (52.26 kt·y))

### Sub-GeV (Fully Contained)

$E_{\text{vis}} < 1.33 \text{ GeV}, P_e > 100 \text{ MeV}, P_\mu > 200 \text{ MeV}$

		Data	MC(Honda flux)	
1ring	e-like	1826	1754.0	$\leftarrow 87\% \nu_e \text{ CC}$
	$\mu$ -like	1852	2617.6	$\leftarrow 95\% \nu_\mu \text{ CC}$
<b>Multi ring</b>		<b>1456</b>	<b>1870.8</b>	
<b>Total</b>		<b>5134</b>	<b>6242.5</b>	

$\frac{(\mu/e)_{\text{Data}}}{(\mu/e)_{\text{MC}}} = 0.680 \begin{matrix} +0.023 \\ -0.022 \end{matrix} \pm 0.053 \quad (5.56 \text{ from 1})$
--

### Multi-GeV

Fully Contained ( $E_{\text{vis}} > 1.33 \text{ GeV}$ )

		Data	MC(Honda flux)	
1ring	e-like	439	414.3	$\leftarrow 80\% \nu_e \text{ CC}$
	$\mu$ -like	351	487.0	$\leftarrow 99\% \nu_\mu \text{ CC}$
<b>Multi ring</b>		<b>867</b>	<b>1079.5</b>	
<b>Total</b>		<b>1657</b>	<b>1980.8</b>	

Partially Contained (assigned as  $\mu$ -like)  $\leftarrow 98\% \nu_\mu \text{ CC}$

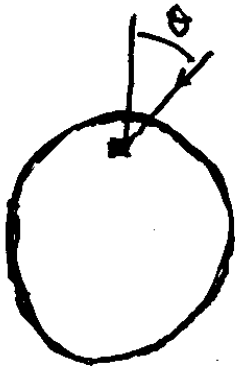
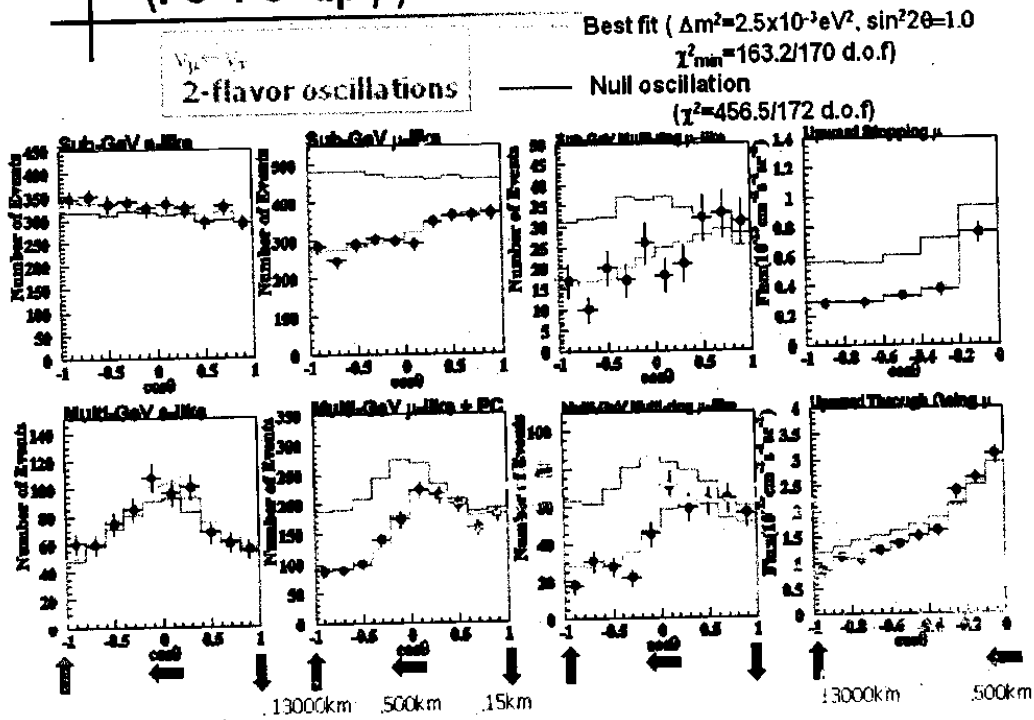
<b>Total</b>	470	656.4
--------------	-----	-------

$\frac{(\mu/e)_{\text{Data}}}{(\mu/e)_{\text{MC}}} = 0.678 \begin{matrix} +0.042 \\ -0.039 \end{matrix} \pm 0.080 \quad (3.65 \text{ from 1})$
--

# SK atmospheric results

May-2002 Neutrino2002 @ Munich

## Zenith angle distributions (FC+PC+up- $\mu$ )



$\cos \theta = 1$  vertical downwards  $\checkmark$

$\cos \theta = -1$  vertical upwards  $\checkmark$

$$\Delta m^2 = 2.5 \cdot 10^{-3} \text{eV}^2 \Rightarrow$$

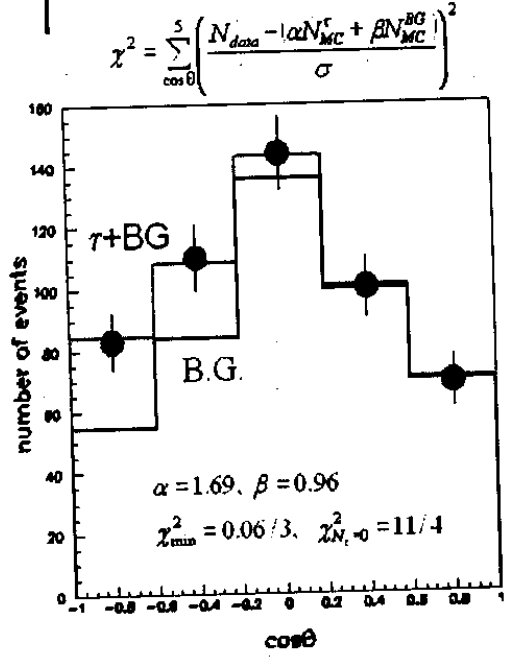
$$L_{\text{osc}} = 1000 \text{ km for } E_\nu = 1 \text{ GeV}$$

OSCILLATION IS MAXIMAL!

$$\nu_\mu \rightarrow \nu_e, \tau, \text{sterile} ?$$

May-2002 Neutrino2002 @ Munich

zenith angle dist. of  $\tau$ -like events



■  $N_{\text{FC}} = \alpha N_{\text{MC}}^{\tau}$  (eff.=0.44)  
 = 145 ± 44 (stat.)  
 + 11 ± 16 (sys.)

$N_{\text{exp}} = 86$

■ consistent with  $\nu_\mu \leftrightarrow \nu_\tau$

■ another analysis gives similar results:

\*analysis-2 (neural network)  
 $N_{\text{FC}} = 99 \pm 39$  (stat.)  
 ± 13 ( $\Delta m^2$ )  
 + 0 / - 16 (3-flavor)

$\nu_\mu \rightarrow \nu_e$  : excluded by CHOOZ and SK

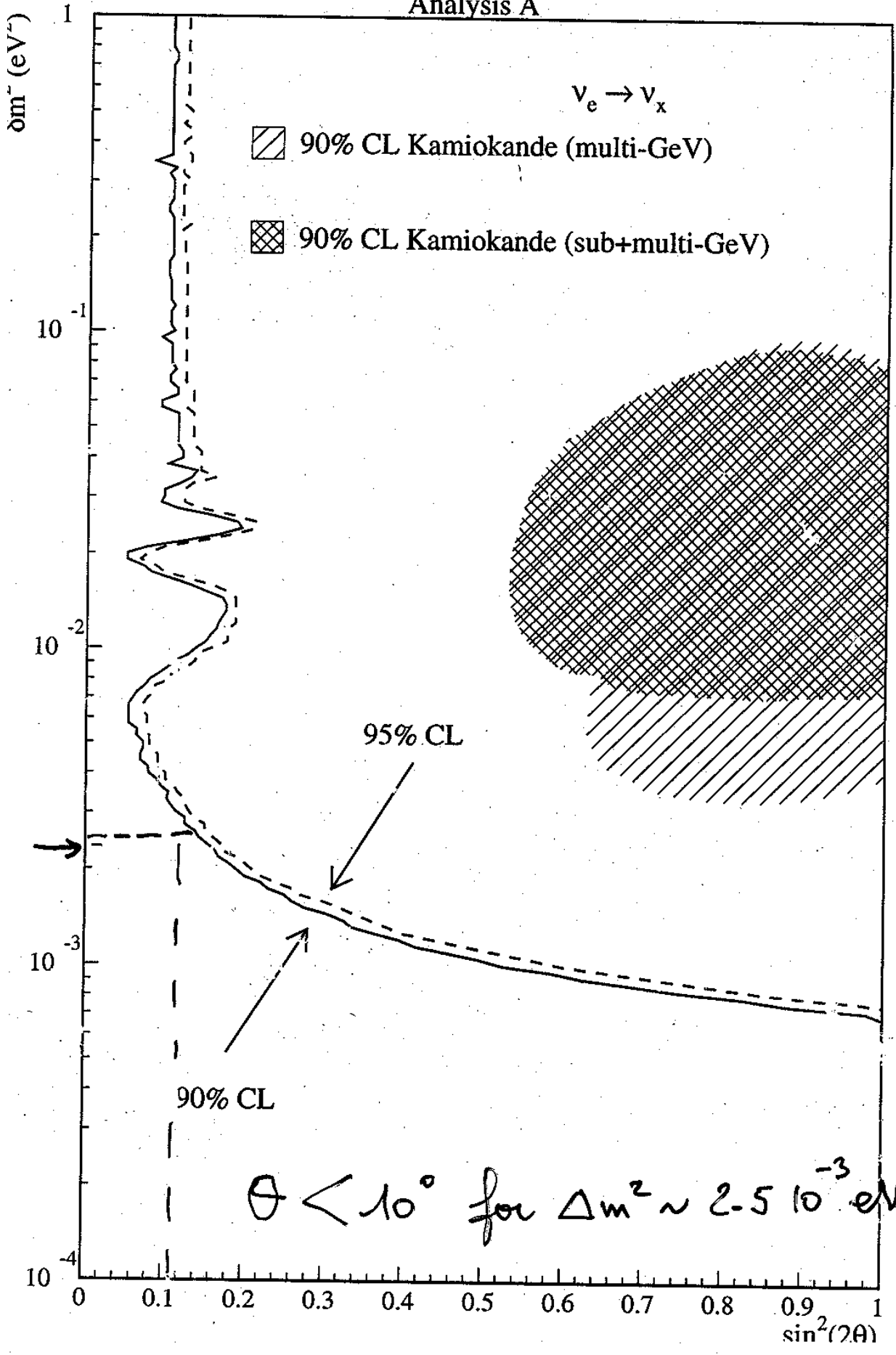
SK: Selection of high energy  $\tau$ -like events favors  $\nu_\mu \rightarrow \nu_\tau$  over  $\nu_\mu \rightarrow \nu_s$

FRACTION OF  $\nu_s < 20\%$  AT  $> 90\%$  CL

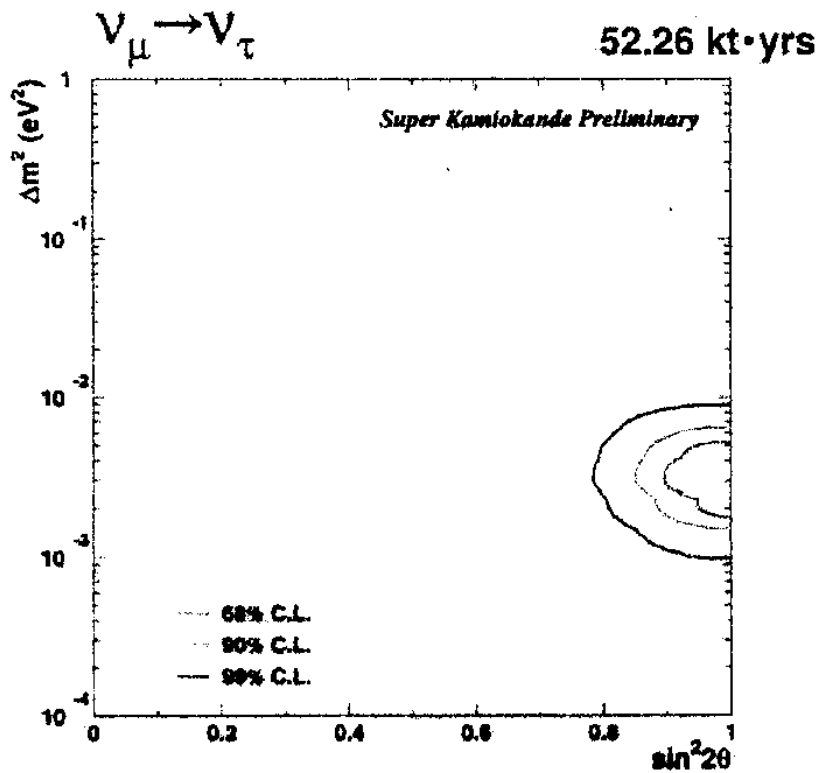
CHOOZ EXPERIMENT



Analysis A



## Allowed region based on contained events



Best fit at  $\Delta m^2 = 3.05 \times 10^{-3} \text{eV}^2$   
 $\sin^2 2\theta = 0.995$

Latest results

$$\Delta m^2 = 2.5 \cdot 10^{-3} \text{eV}^2$$

$$\sin^2 2\theta = 1.0$$

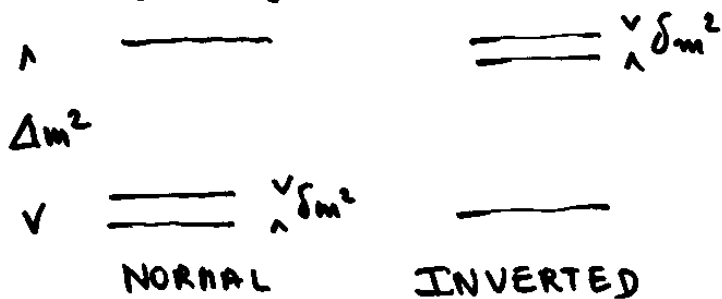
## Why test for sterile neutrinos?

- We already found 2 oscillation frequencies

$$\delta m^2 \sim 7 \cdot 10^{-5} \text{ eV}^2$$

$$\Delta m^2 \sim 2.5 \cdot 10^{-3} \text{ eV}^2$$

There is no room left for other frequencies if only 3 neutrinos



But in 1993-98, the LSND experiment

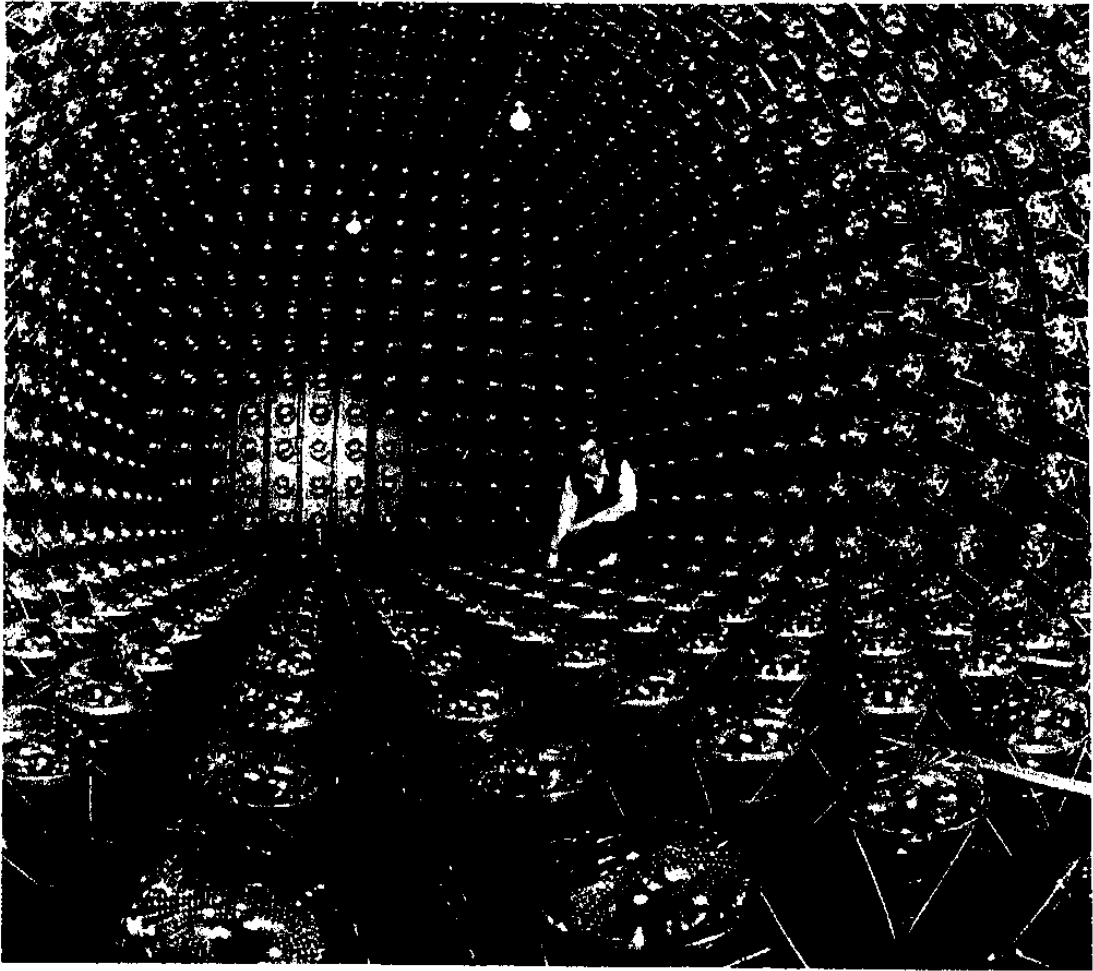
has seen a signal for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillation with  $\Delta m^2 > 0.2 \text{ eV}^2$

If true, one needs (at least)

4 types of neutrinos

1 is sterile since only 3 are coupled to the  $Z^0$

# LSND

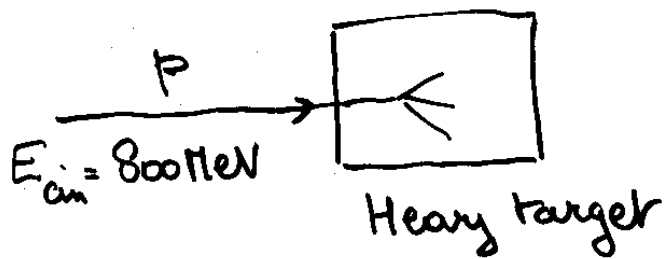


diluted liquid scintillator ( $167\text{m}^3$ )

Scintillation +  $\checkmark$  light

$\Rightarrow$  Directionality,  
Particle identification

# LSND $\nu$ BEAM



Production of  $\pi^+$  and  $\pi^-$

$\pi^-$  get absorbed by nuclei ( $\pi$ -mesic atoms)

$\pi^+$  decay at rest:

$$\pi^+ \rightarrow \mu^+ \nu_{\mu} \quad (30 \text{ MeV})$$

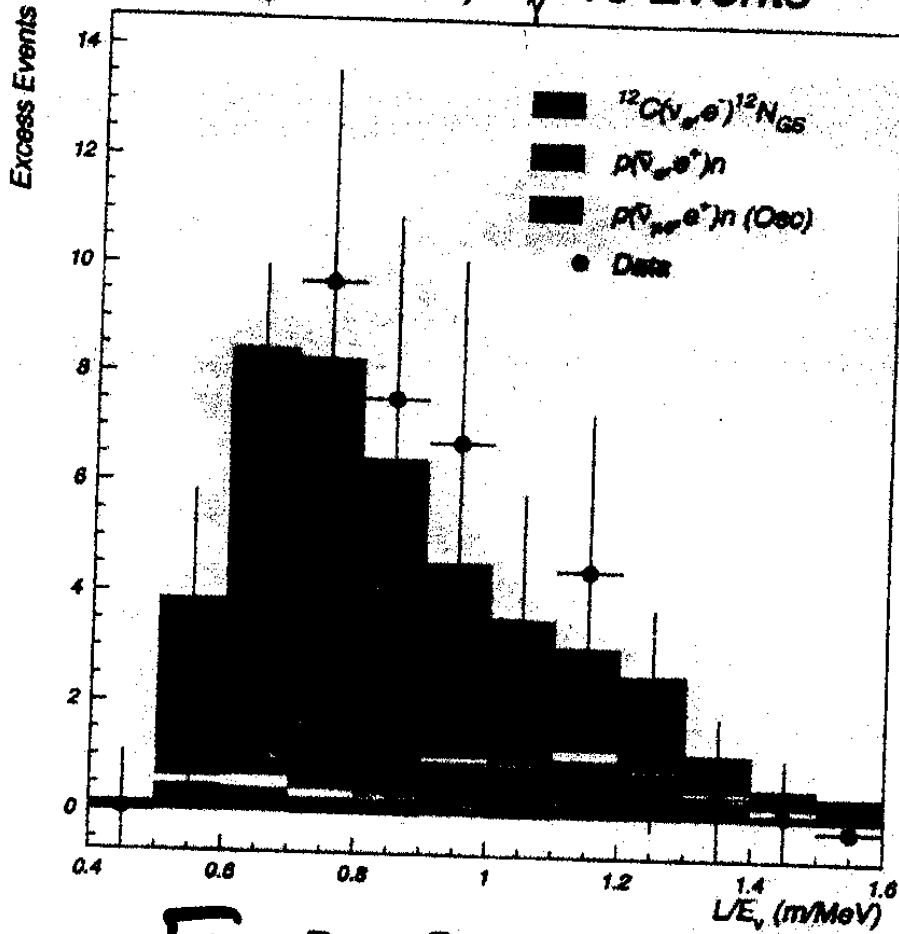
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_{\mu}$$

$\Rightarrow$  No  $\bar{\nu}_e$  are produced

If  $\bar{\nu}_e$ 's are detected, they most probably come from

$$\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e \text{ oscillation}$$

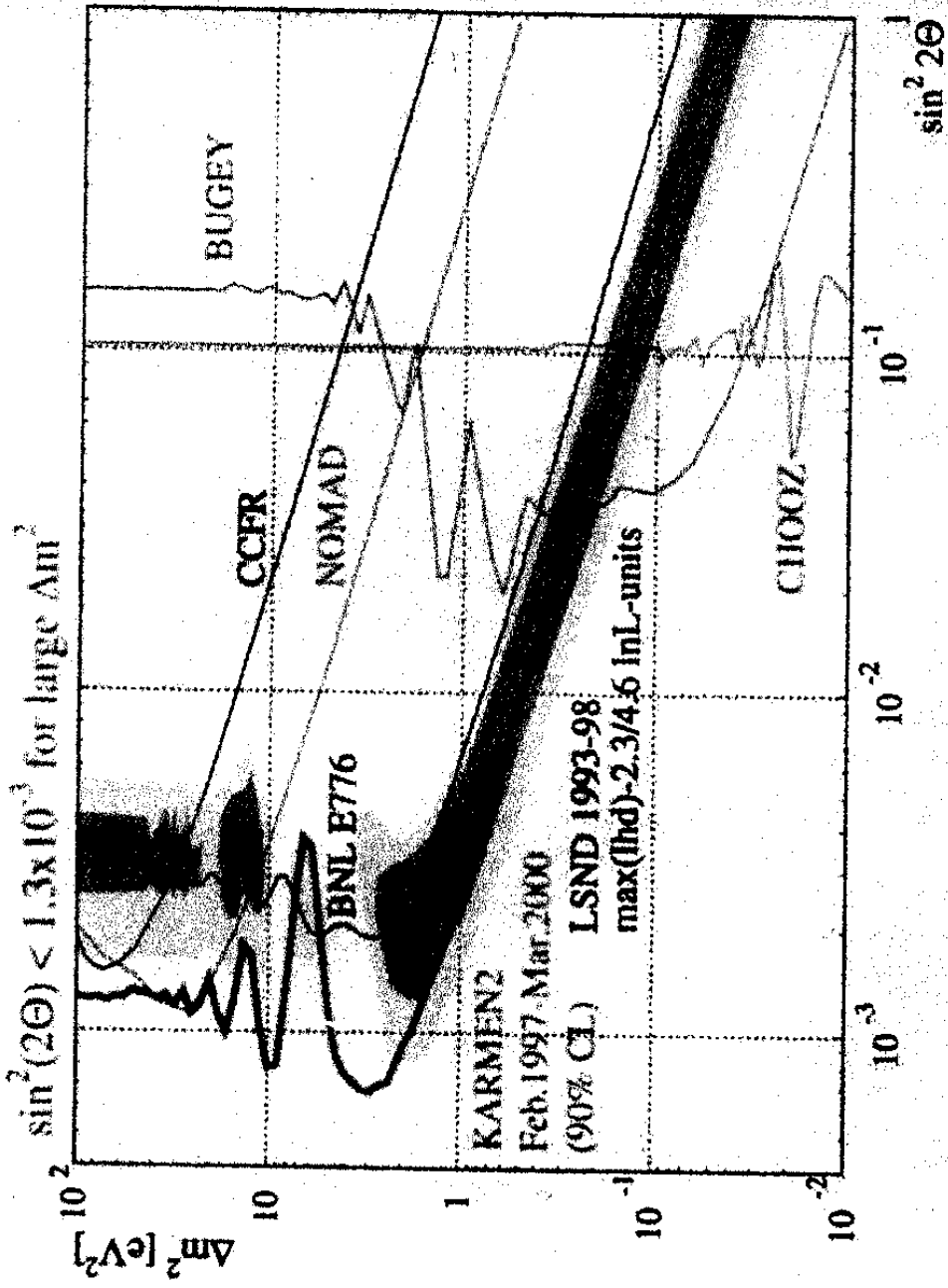
' $\theta+\gamma$ ' events,  $R_\gamma > 10$  Events



Excess  $32.7 \pm 9.2$

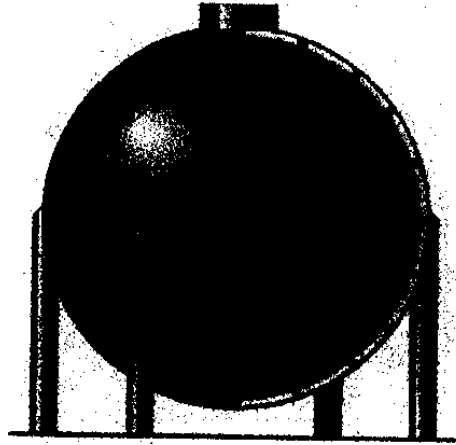
$P_{02} = 0.25 \pm 0.06 \pm 0.04 \%$

# neutrino oscillation plot



Eitel - 10

## MiniBooNE detector



Pure mineral oil

total volume: 800 tons (20 foot radius)

fiducial volume: 445 tons (5 m radius)

1280 PMTs in detector at 5.5 m radius

→ 10% photocathode coverage

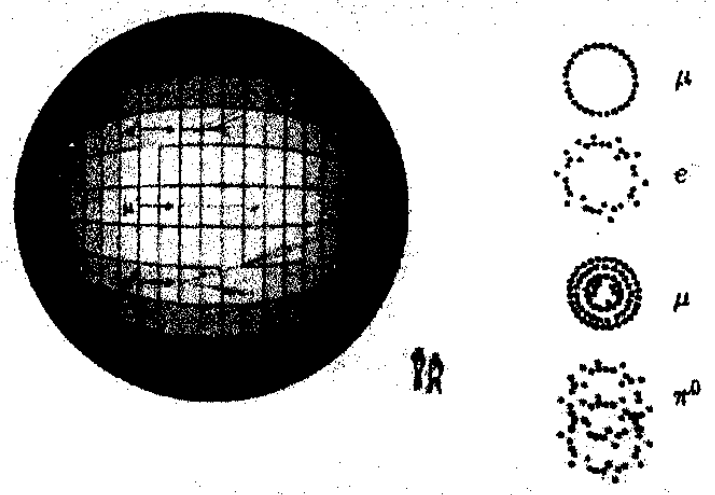
240 PMTs in veto

Phototube support structure provides an opaque barrier between veto and main volumes

main volume black

veto volume white

### Analysis: $e, \mu, \pi^0$ discrimination



- PID based on ring id, track extent, ratio of prompt/late light  
 Signatures substantially different from LSND due to
- $\times 10$  higher energy
  - very little scintillation light in QE event (pure oil)  
 Cherenkov to scintillation light ratio 4:1
  - neutron capture is not part of the signature

if LSND correct:  $\sim 500$  events or more (1 year)

backgrounds are mix-td of  $\mu$ 's and  $\pi^0$ 's, and intrinsic  $\nu_e$  in the beam

Si LSND correct

$\nu_e$  event  $> 500$  events

IF LSND correct

## Confirmation of SK results with accelerators

- The neutrino community has felt the necessity to confirm the  $\nu_\mu \leftrightarrow \nu_\tau$  maximal oscillation seen by SK
- Use a  $\nu_\mu$  beam from accelerator of known energy with low contamination
- Observe  $\nu_\mu$  disappearance and determine  $\Delta m^2, \sin^2 2\theta$
- Observe (if possible)  $\nu_\tau$  appearance

SK oscillation is maximal at

$$L/E = 500 \text{ km/GeV}$$

$\Rightarrow$  long baseline experiments

### 3 PROJECTS WORLDWIDE

#### 1 - K2K (KEK to Kamioka)

$$E_\nu \sim 1 \text{ GeV}, L = 250 \text{ km}$$

Takes data, published first results

Low intensity beam  $\Rightarrow$  low statistics

#### 2 - MINOS (USA) FNAL $\rightarrow$ SOUDAN

$$E_\nu \sim 3 \text{ GeV}, L = 730 \text{ km}$$

Detection ready, beam in 2005

Cannot see  $\nu_\tau$  CC

#### 3 - CNGS (CERN to GRAN SASSO)

$$E_\nu \sim 20 \text{ GeV}, L = 730 \text{ km}$$

$L/E$  very small, but  $\nu_\tau$  can interact

Beam in 2006

2 detectors optimized to detect

$\nu_\tau$  interactions

ICARUS : liquid Argon TPC

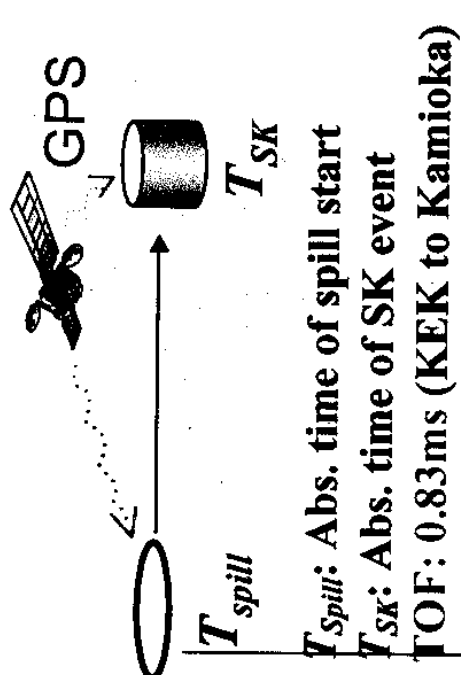
OPERA : lead and emulsions

are under construction



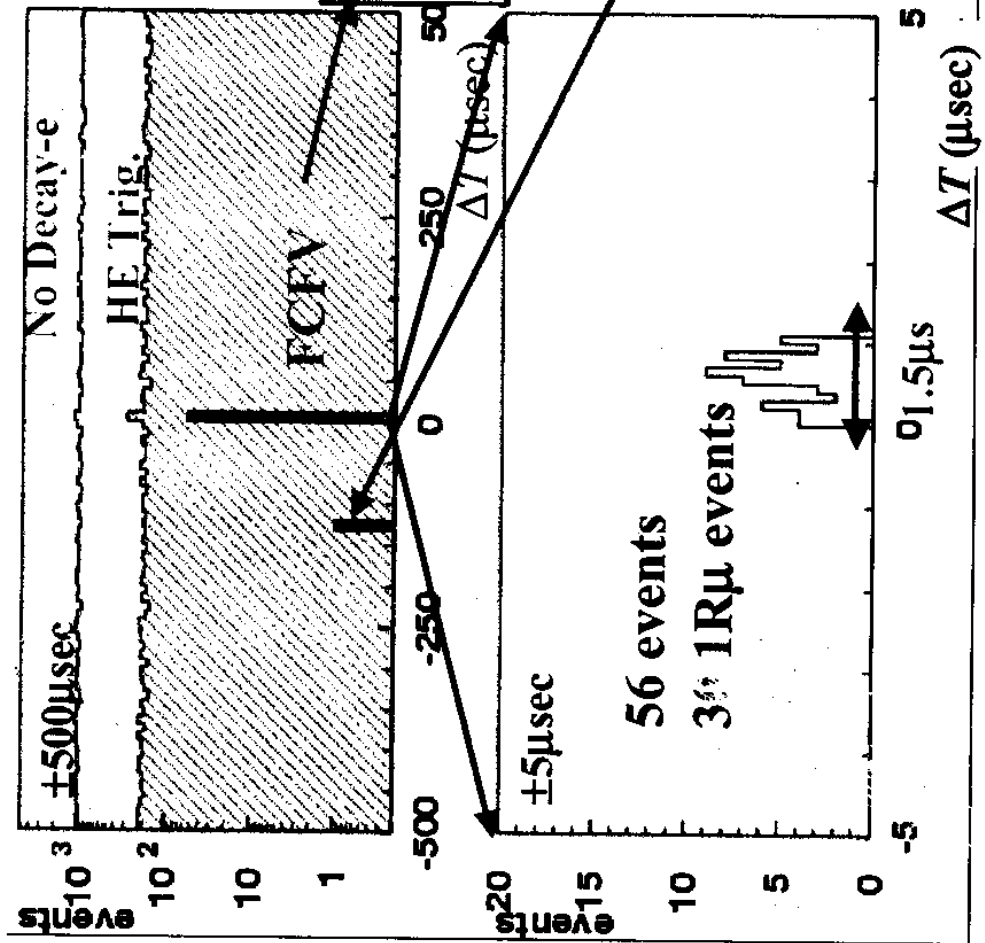
# Super-K Event selection

$$-0.2 \leq \Delta T \equiv T_{SK} - T_{Spill} - TOF \leq 1.3 \mu\text{sec}$$



FC: fully contained  
 (No activity in Outer Detector)  
 FV: 22.5kt Fiducial Volume

Expected Atm.  $\nu$  BG  
 $< 10^{-3}$  within 1.5 $\mu$ s.



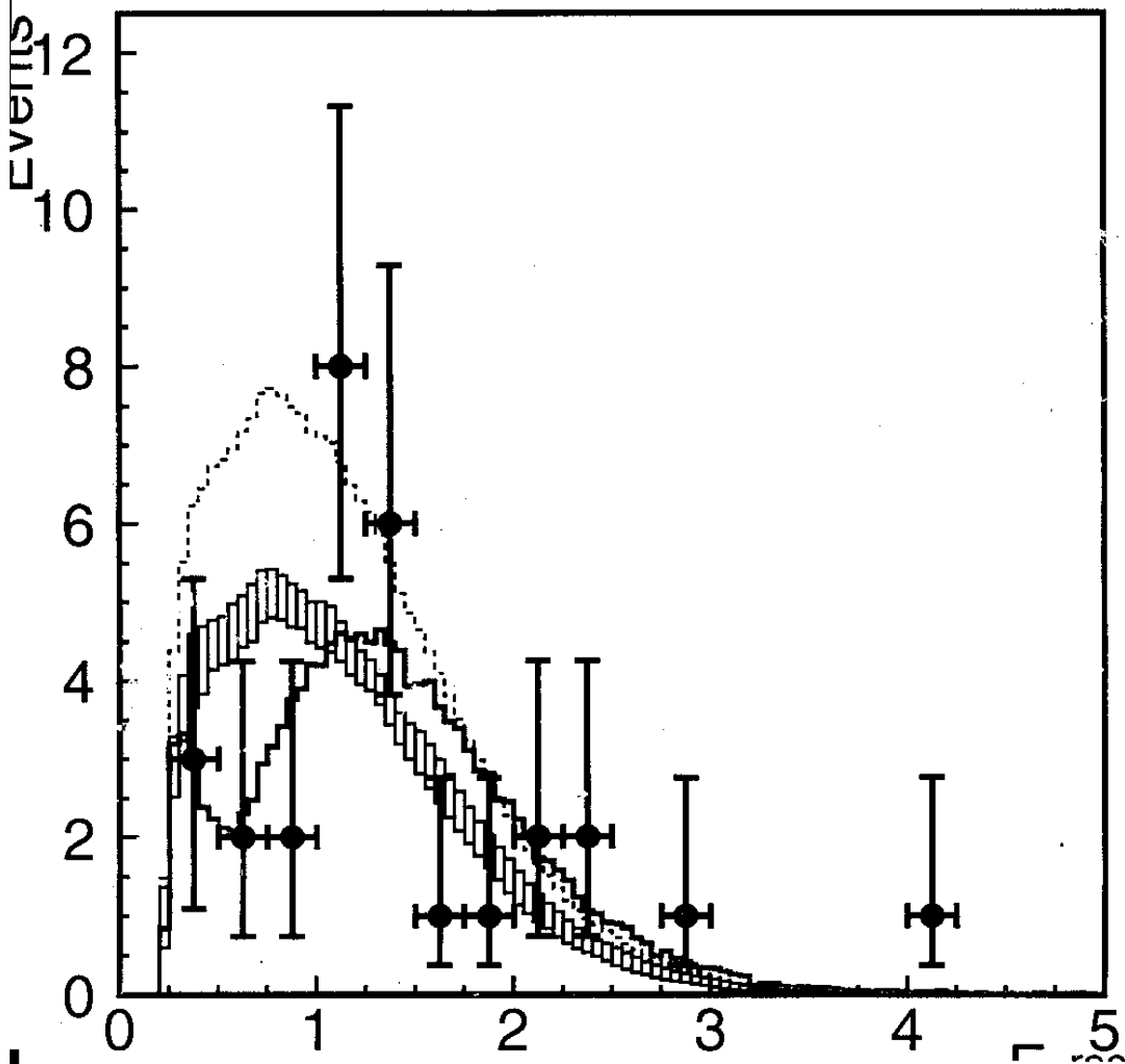
K2K Décembre 2002

$\nu_\mu$  attendus : 80 . expected  $\nu_\mu$

$\nu_\mu$  vus : 56 seen  $\nu_\mu$

⇒ l'oscillation des neutrinos  
atmosphériques est confirmée !

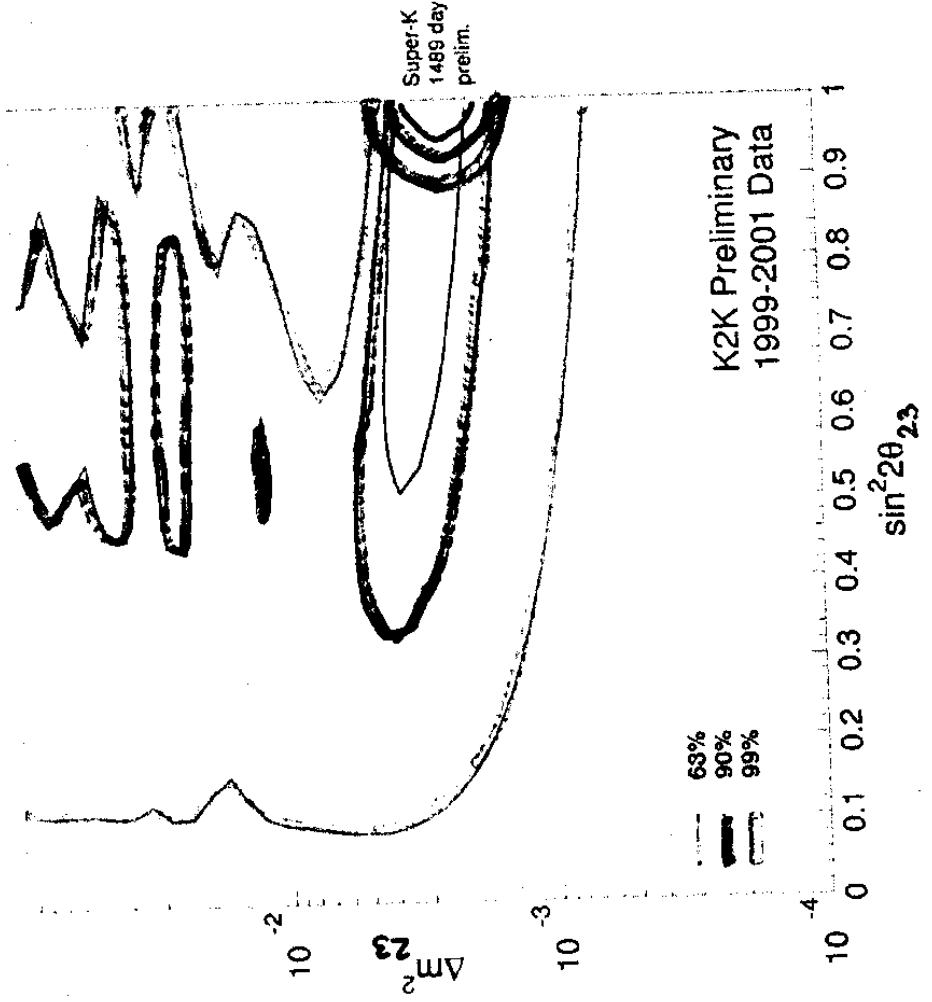
SK result is confirmed



# PERFECT AGREEMENT

## Comparison with SK atm $\nu$ observation

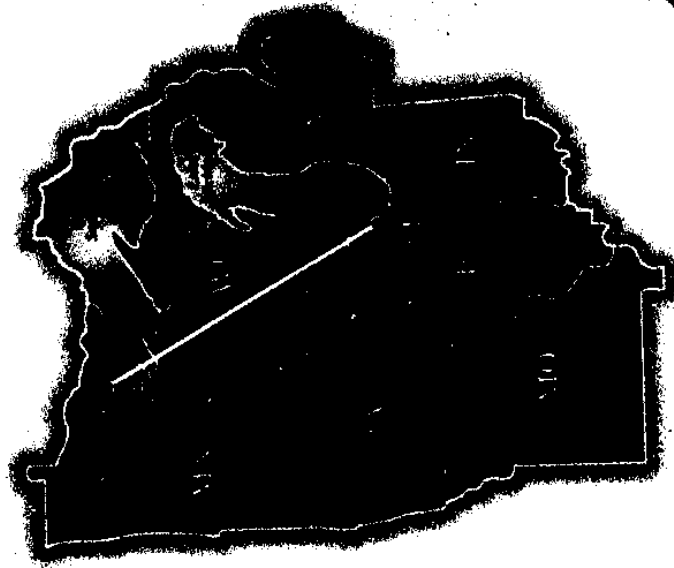
Allowed Region - Total Number + Shape



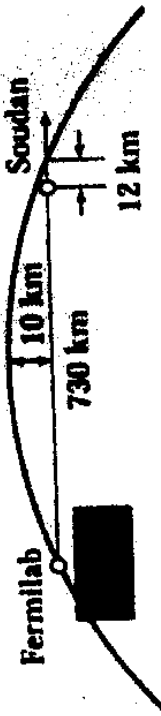


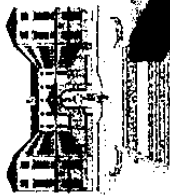
# MINOS Experiment

## Two Detector Neutrino Oscillation Experiment (Start 2003)



Near Detector: 980 tons  
Far Detector: 5400 tons

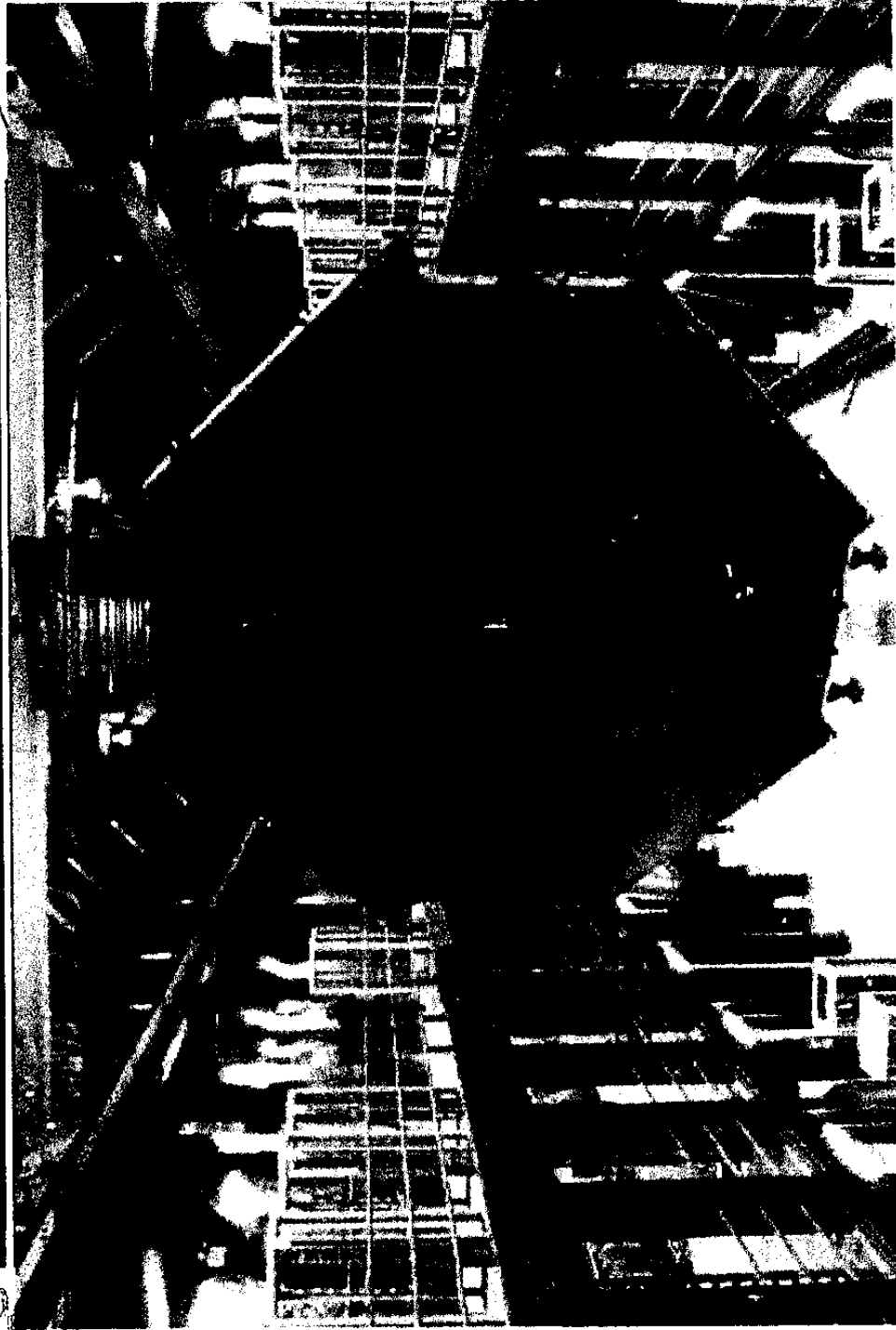




*2<sup>me</sup> colloque Neutrino du Troisième millénaire  
Collège de France, 22/01/2002*

# MINOS : installation

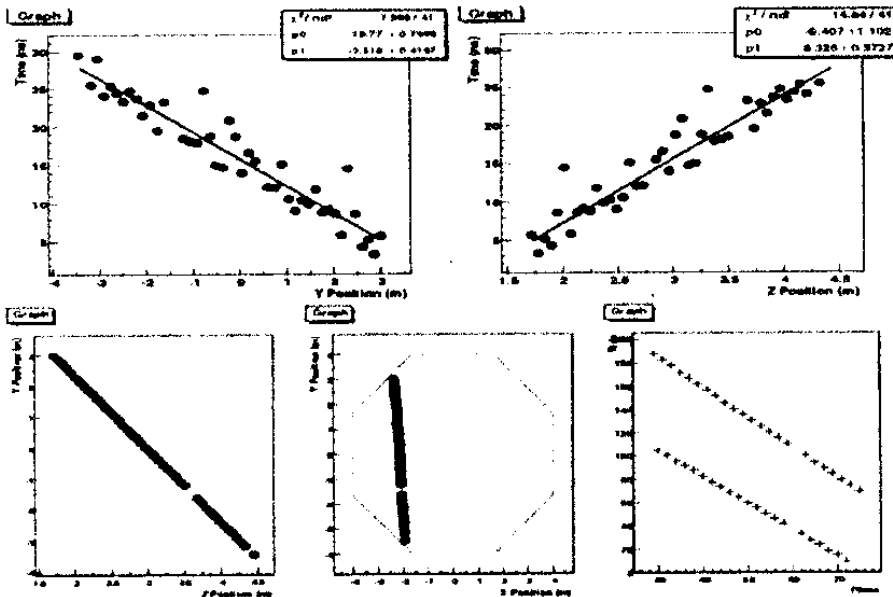
PL



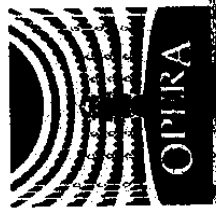
1<sup>er</sup> plan

# Cosmic Ray Muon in the Far Detector

- Downgoing Cosmic Ray Muon
- Current rate of CR muons  $\sim 2$  Hz
- Magnetic field not yet on (curvature measurable up to  $\sim 70$  GeV)

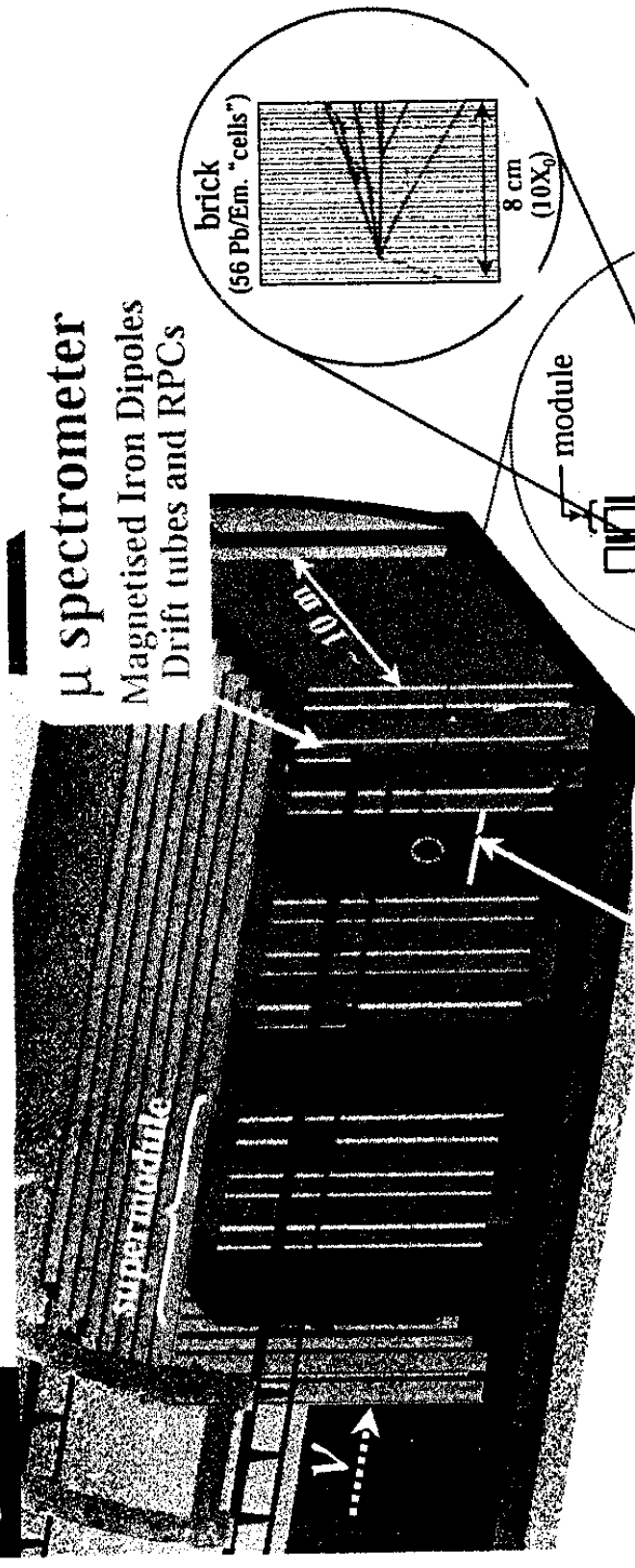






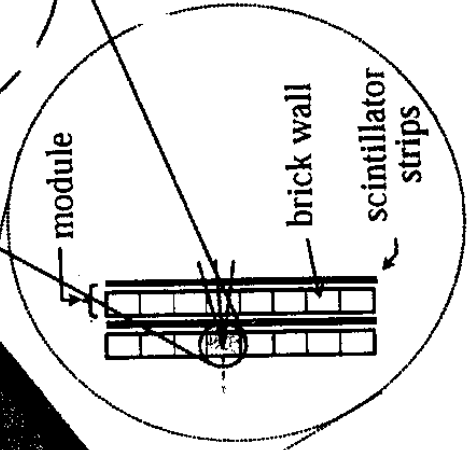
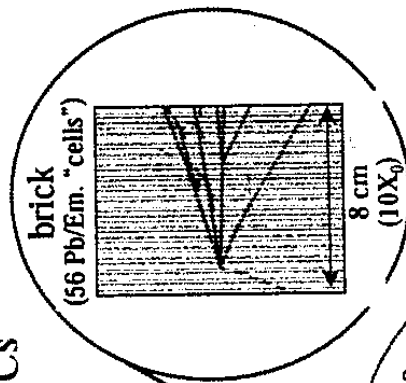
# The detector at Gran Sasso

(modular structure, configuration with three "supermodules")



## $\mu$ spectrometer

Magnetised Iron Dipoles  
Drift tubes and RPCs

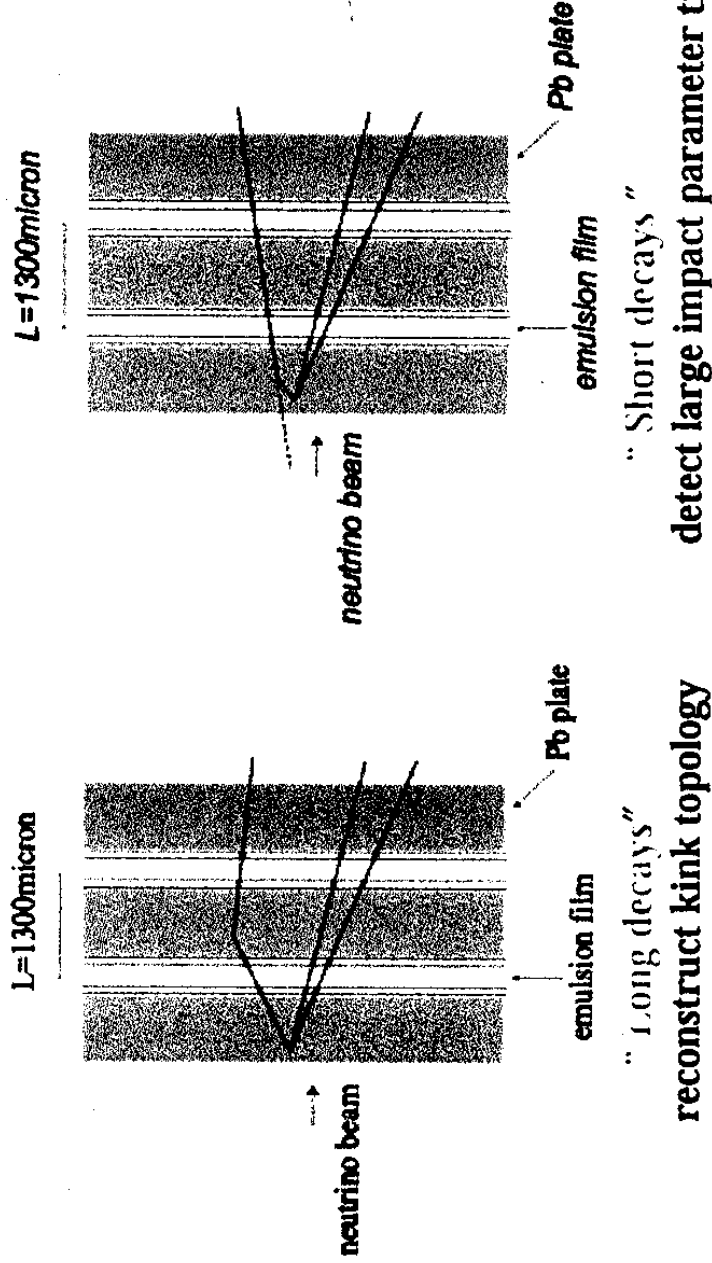


## $\nu$ target and $\tau$ decay detector

- Each "super module" is a sequence of 24 "modules" consisting of
- a "wall" of Pb/emulsion "bricks"
- planes of orthogonal scintillator strips



# Select $\nu_\tau$ candidates to be passed to the FULL data taking

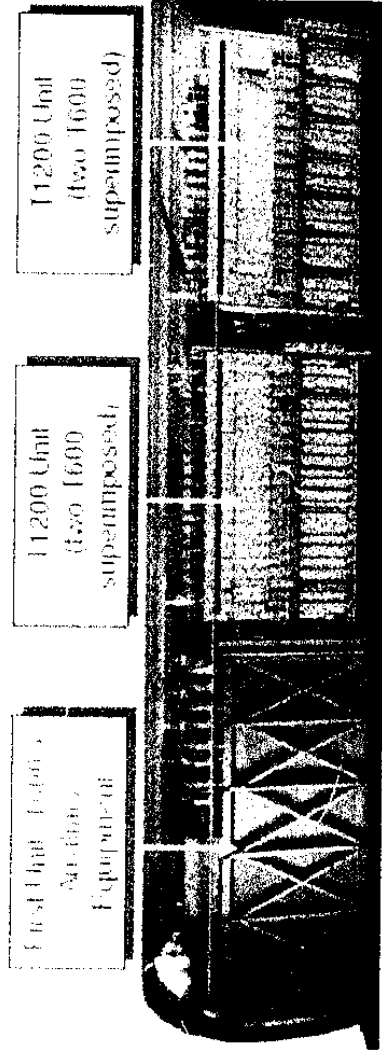


Loose cut to reject low momentum tracks

Small fraction of the beam events are passed to the FULL DATA

# ICARUS T3000 (proposed)

T3000 Detector in Hall B of LNGS (cloning of T600)



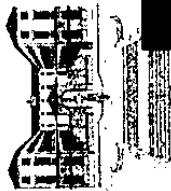
Improved statistics for:  $\approx$  70 Metres

Future extension  
to additional modules

1. Solar neutrinos
2. Atmospheric neutrinos
3. Supernova neutrinos
4. CERN-NGS neutrinos
5. Proton decay

T600: installed in LNGS in 2003

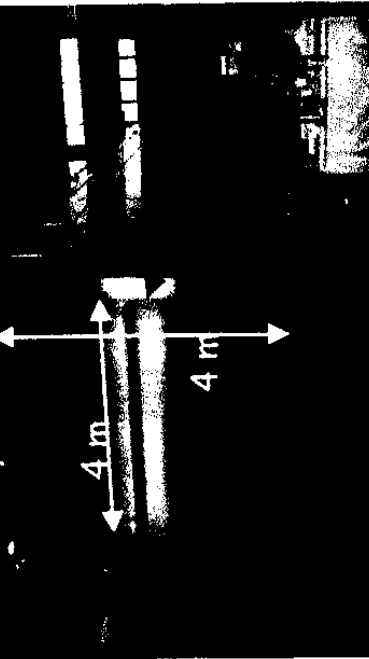
T3000: operational by summer 2006



# ICARUS T600

PL

LAr Cryostat (half-module)



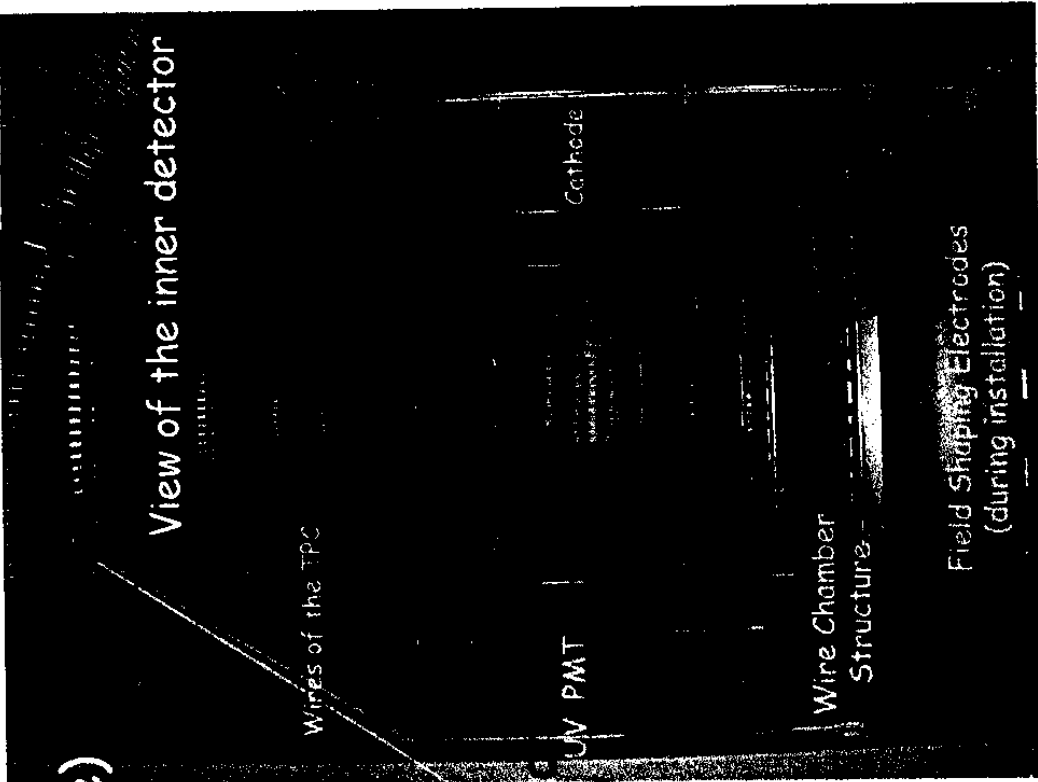
Detector during construction



Electronic Racks

Signal Flanges and feed-throughs

View of the inner detector



Wires of the TPC

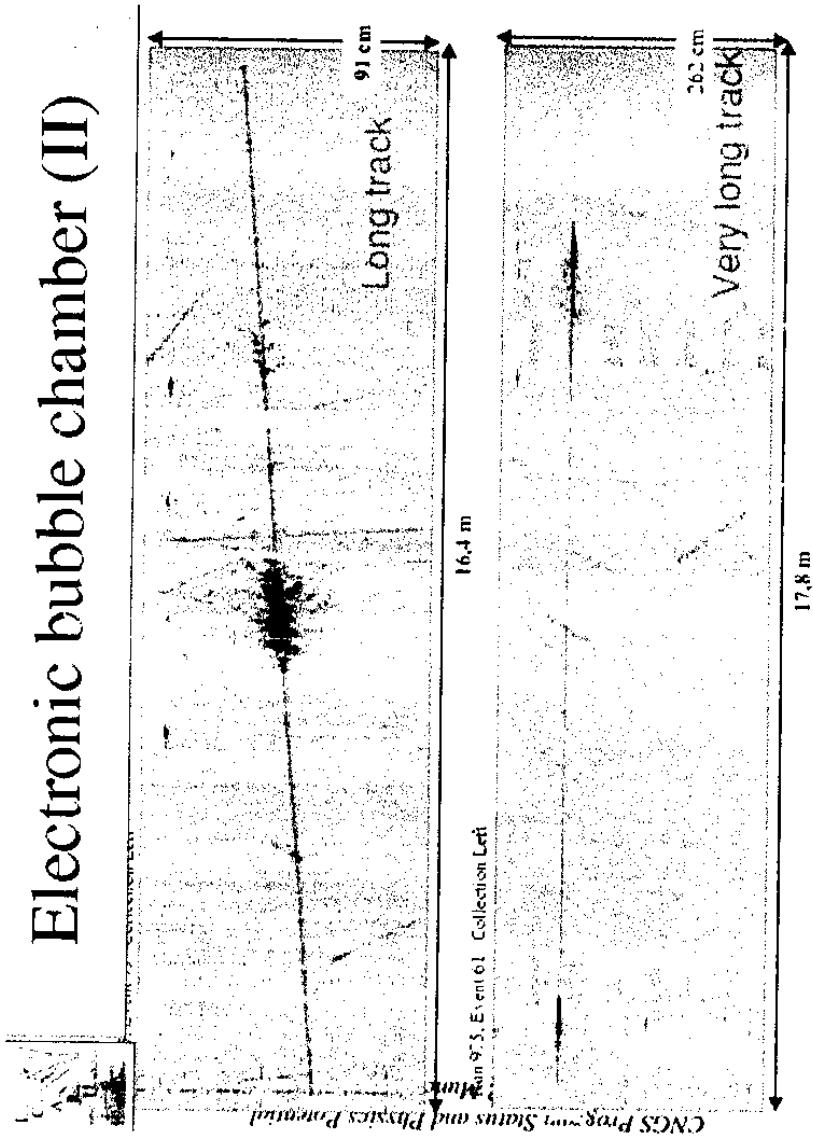
UV PMT

Cathode

Wire Chamber Structure

Field Shaping Electrodes (during installation)

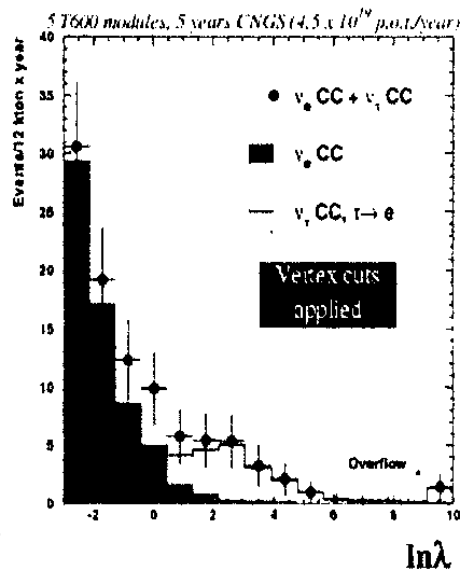
# Electronic bubble chamber (II)





## $\tau \rightarrow e$ search: 3D likelihood

- Analysis based on 3 dimensional likelihood
  - $E_{\text{visible}}$
  - $P_{\tau}^{\text{miss}}$
  - $\rho_1 \equiv P_{\tau}^{\text{lep}} / (P_{\tau}^{\text{lep}} + P_{\tau}^{\text{had}} + P_{\tau}^{\text{miss}})$
  - Exploit correlation between variables
  - Two functions built:
    - $L_S$  ( $(E_{\text{visible}}, P_{\tau}^{\text{miss}}, \rho_1)$ ) (signal)
    - $L_B$  ( $(E_{\text{visible}}, P_{\tau}^{\text{miss}}, \rho_1)$ ) ( $\nu_e$  CC background)
  - Discrimination given by



$$\ln \lambda \equiv L([E_{\text{visible}}, P_{\tau}^{\text{miss}}, \rho_1]) = L_S / L_B$$

For  $\Delta m^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$ ,

each experiment expects to see

10  $\nu_e$  CC candidates

with a background  $< 1 \text{ ev}$

in 5 years data taking

7

### 3 flavor mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad \begin{array}{l} \nu \leftrightarrow \bar{\nu} \\ U \leftrightarrow U^* \end{array}$$

$$|\nu_\ell(t)\rangle = \sum_i U_{\ell i} e^{-iE_i t} |\nu_i\rangle$$

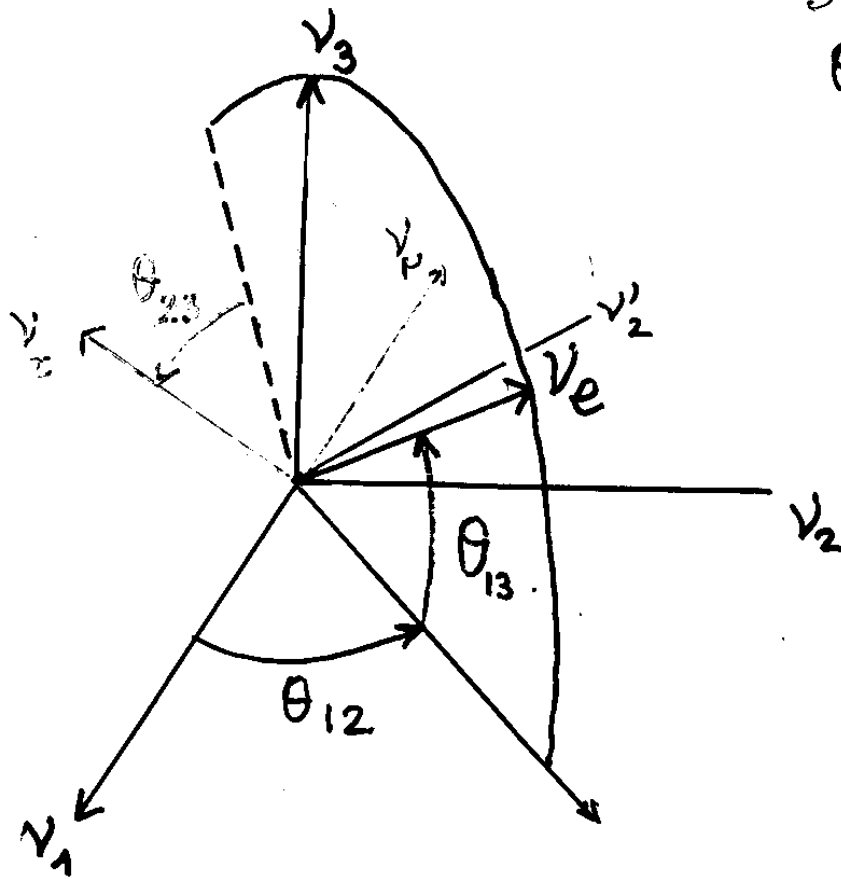
$$\langle \nu_{\ell'} | \nu_\ell(t) \rangle = \sum_i U_{\ell' i}^* U_{\ell i} e^{-iE_i t}$$

$$P_{\ell\ell'}(t) = \sum_{i>j} U_{\ell' i}^* U_{\ell i} U_{\ell' j} U_{\ell j}^* e^{-i(E_i - E_j)t}$$

$$= \sum_i |U_{\ell i}|^2 |U_{\ell' i}|^2$$

$$+ 2 \operatorname{Re} \sum_{i \neq j} (U_{\ell i} U_{\ell' i}^* U_{\ell' j}^* U_{\ell j}) \cos(E_i - E_j)t$$

$$+ 2 \operatorname{Im} \sum_{i \neq j} (U_{\ell i} U_{\ell' i}^* U_{\ell' j}^* U_{\ell j}) \sin(E_i - E_j)t$$



• mixing angles:  
 $\theta_{12}, \theta_{13}, \theta_{23}$

$$U = R_{1''}(\theta_{23}) \begin{pmatrix} 1 & & \\ & 1 & \\ & & e^{i\delta} \end{pmatrix} R_{2'}(\theta_{13}) R_3(\theta_{12}) \begin{pmatrix} 1 & & \\ & e^{i\phi_1} & \\ & & e^{i\phi_2} \end{pmatrix}$$

CP phase Majorana phase

- Note: Majorana phases are null for Dirac  $\nu$ 's  
 They do not enter oscillation formulae  
 The phase  $\delta$  may exist for Dirac and  
 for Majorana - It enters oscillation  
 formulae and induces CP violation

$$= \begin{pmatrix} c_{13} c_{12} & c_{13} s_{12} & s_{13} \\ -s_{12} c_{23} - c_{12} s_{13} s_{23} e^{i\delta} & c_{12} c_{23} - s_{12} s_{13} s_{23} e^{i\delta} & c_{13} s_{23} e^{i\delta} \\ s_{12} s_{23} - c_{12} s_{13} c_{23} e^{i\delta} & -c_{12} s_{23} - s_{12} s_{13} c_{23} e^{i\delta} & c_{13} c_{23} e^{i\delta} \end{pmatrix}$$

$$c_{ij} = \cos \theta_{ij} \quad s_{ij} = \sin \theta_{ij}$$

Atmospheric frequency ( $\Delta m^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$ )

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{23} t$$

$$\text{CHOOZ expt: } \sin^2 2\theta_{13} < 0.1$$

$$\boxed{\theta_{13} < 10^\circ}$$

$$P_{\mu\tau} = c_{13}^4 \sin^2 2\theta_{23} \sin^2 \Delta_{23} t$$

$$\text{CHOOZ } c_{13}^4 > 0.97$$

$$\text{SK } \sin^2 2\theta_{23} \sim 1$$

$$\boxed{\theta_{23} \sim 45^\circ}$$

Solar frequency in vacuum (KamLand)

$$P_{ee} = \underbrace{(c_{13}^4 + s_{13}^4)}_{\sim 1 \text{ from CHOOZ}} - \underbrace{c_{13}^4}_{\sim 1} \sin^2 2\theta_{12} \sin^2 \Delta_{12} t$$

$\sim 1$  from CHOOZ

KamLand + solar expts  $\Rightarrow$

$$\boxed{\theta_{12} \sim 33^\circ}$$

OSCILLATIONS  
WITH  
SUPER BEAMS

{ DIRECT MASS MEAS<sup>2</sup>  
OV BB  
Very LBL

} BB OV

# WHAT WE KNOW, AND WHAT WE WANT TO KNOW

- Mixing matrix:

$$\theta_{23} \sim 45^\circ \quad \theta_{12} \sim 33^\circ$$

$$\theta_{13} < 10^\circ \quad \delta \text{ unknown}$$

- Masses

$$m_2^2 - m_1^2 = 7 \cdot 10^{-5} \text{ eV}^2$$

$$|m_3^2 - m_1^2| = 2.5 \cdot 10^{-3} \text{ eV}^2$$

Absolute mass scale and hierarchy

$$3 \text{ --- } \underline{\underline{2}}_1 \text{ } \equiv \equiv$$

$$\underline{\underline{2}}_1 \text{ --- } 3$$

NORMAL

INVERTED

DEGENERATE

$$m < 2.2 \text{ eV}$$

$$(m < 0.23 \text{ eV}?)$$

- Neutrino nature

- Dirac or Majorana?

- If Majorana, Majorana phase

## DETERMINING $\theta_{13}$ and $\delta$

First possibility = Try to improve

CHOOZ result (SuperCHOOZ projects)

- Use 2 identical detectors and compare them to decrease systematics below 1% (CHOOZ systematics = 2.7%)  
No sensitivity to CP violation

Second possibility =

Try to measure  $\nu_{\mu} \leftrightarrow \nu_e$  oscillation at the atmospheric frequency

→ Appearance rather than disappearance

In principle sensitive to much smaller oscillations

CP violation can be seen comparing  $\nu$  and  $\bar{\nu}$  oscillations

Main problem is the smallness of this oscillation (we don't even know if it exists!)

→ Need intense  $\nu$  beams and massive detectors

## The ideal tool = the neutrino factory

Idea = Produce, accelerate (20 to 50 GeV) and store muons in a storage ring pointing towards a distant detector. Muon decays produce a neutrino beam:

$$\mu^- \rightarrow \nu_\mu, \bar{\nu}_e \quad \text{No } \bar{\nu}_\mu$$

$$\Rightarrow \text{Detect } \bar{\nu}_\mu \times \rightarrow \mu^+ \times$$

WRONG SIGN MUONS

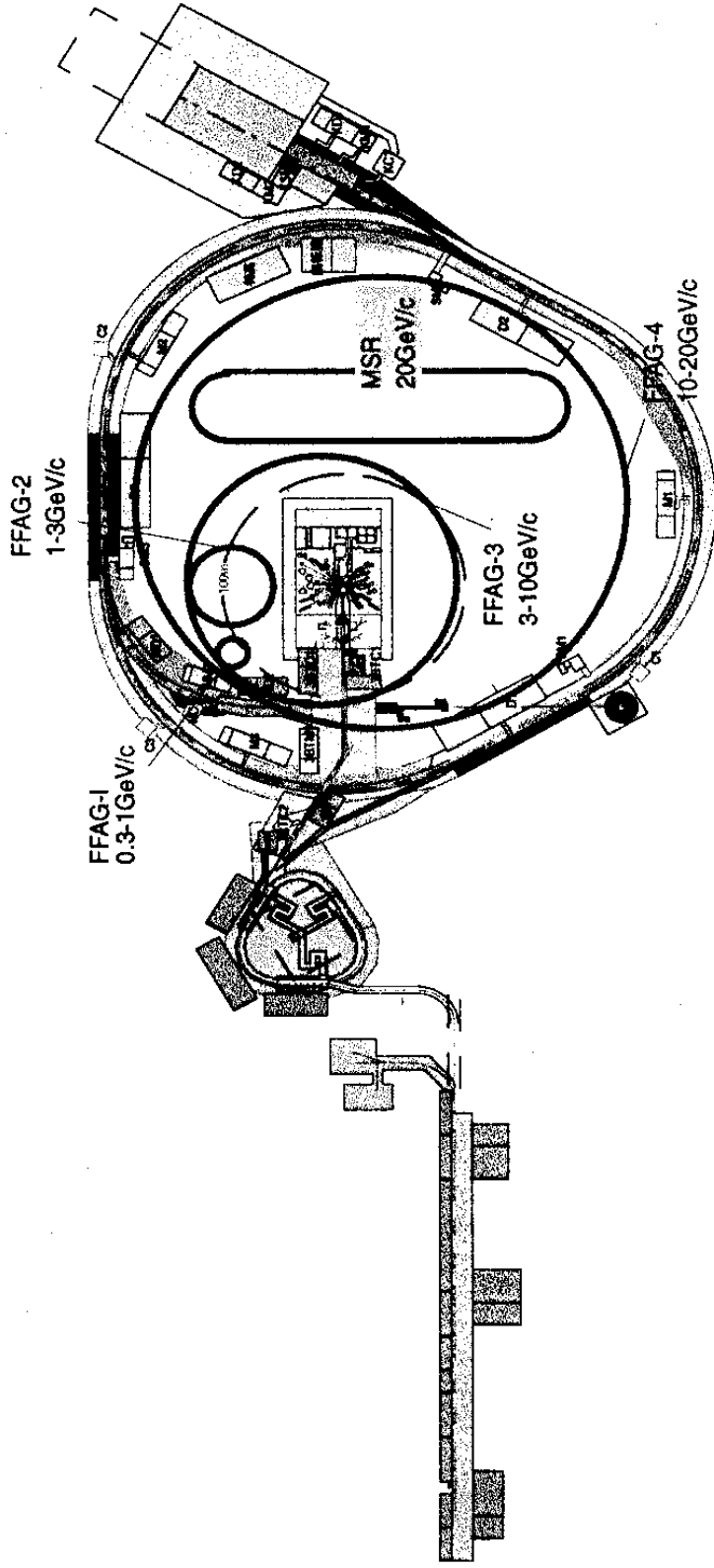
→ Massive magnetized detector

Repeat with  $\mu^+$  and compare

\* Sensitivity to true CP is complicated due to matter effects generating fake CP violation

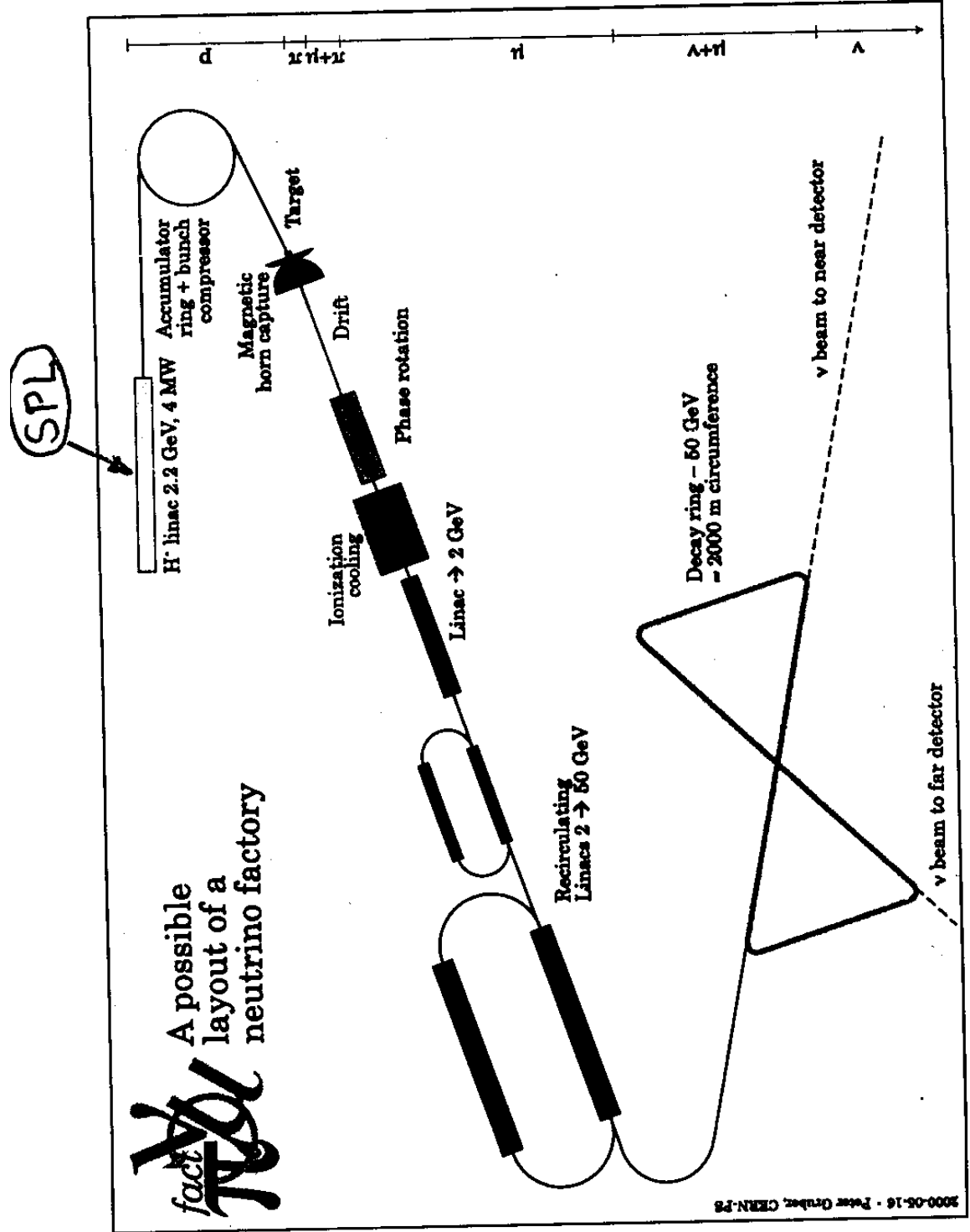
These matter effects however give directly the mass hierarchy (normal / inverted)

# FFAG based Neutrino Factory



$10^{23}$  protons  
per am.

(4)

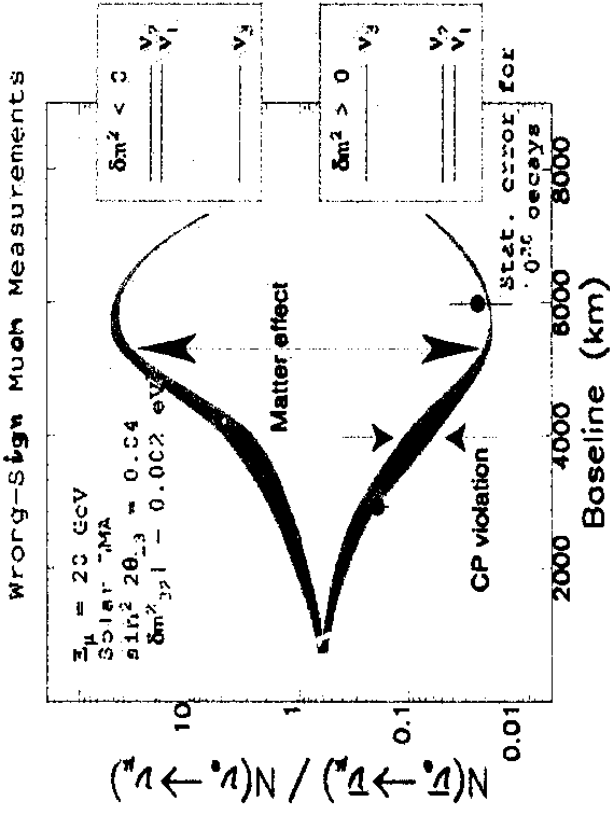


A possible layout of a neutrino factory

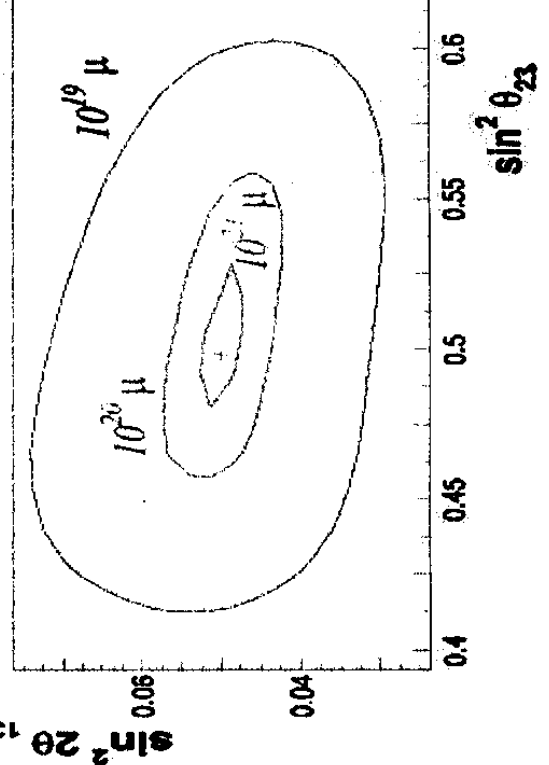
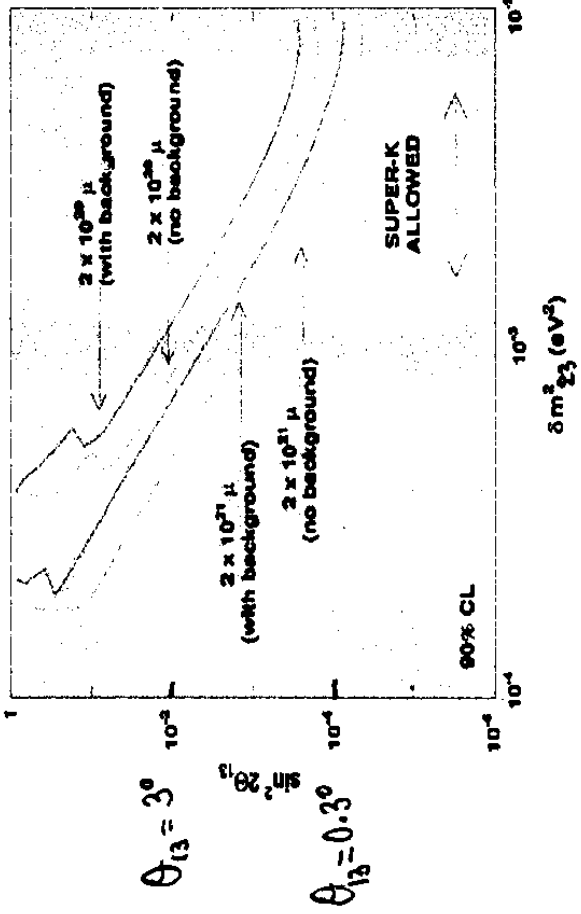
A neutrino factory with 1020 muons/y would:

- 1) determine  $\theta_{13}$
- 2) measure CP violation
- 3) determine the sign of mass difference

hep-ex/0008064 and european studies but see Sato/Richter proposition of an intense conventional beam.....



$E_\mu = 30 \text{ GeV}$ ,  $L = 7400 \text{ km}$ ,  $\Delta m_{32}^2 = 3.5 \times 10^{-3} \text{ eV}^2$  fixed  $\rho$



## CP phase is well hidden in the mixing matrix

In principle CP terms could be extracted with oscillations from the first and the third generation ( $\nu_e \rightarrow \nu_\tau$ ), in practice this experimental approach seems non viable: too difficult to detect  $\nu_\tau$  in very massive detectors.

Best possibility:  $\nu_\mu \rightarrow \nu_e$  transitions.

$$P(\nu_\mu \rightarrow \nu_e) =$$

$$\begin{aligned}
 & 4c_{13}^2 s_{12}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \quad \theta_{13} \text{ driven} \\
 & + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CP - even} \\
 & - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CP - odd} \\
 & + 4s_{12}^2 c_{13}^2 \{ c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta \} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driven} \\
 & - 8c_{13}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} (1 - 2s_{13}^2) \quad \text{matter effect (CP odd)}
 \end{aligned} \tag{1}$$

Where  $a = \pm 2\sqrt{2}G_F n_e E_\nu = 7.6 \cdot 10^{-5} \rho [g/cm^3] E_\nu [GeV]$  [eV<sup>2</sup>]

At the first order, neglecting matter effects and CP:

$$P(\nu_\mu \rightarrow \nu_e) \propto \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m_{23}^2 L}{4E}$$

## CP violation and LMA

The CP odd term is proportional to

$$J = \sin\theta_{12} \sin\theta_{23} \sin\theta_{13} \frac{\Delta m_{\text{sun}}^2}{\Delta m_{\text{atm}}^2}$$

In order to give visible effects in  $\nu_{\mu} \leftrightarrow \nu_e$ , it was imperative that both  $\sin\theta_{12}$  and  $\frac{\Delta m_{13}}{\Delta m_{23}}$  be as big as possible

In practice, only LMA solution was fit.

Nature has been kind!

But... we don't know how small  $\sin\theta_{13}$  is. It could even be  $=0$ !

So, probably no neutrino factory will be built unless one proves beforehand that the  $\nu_{\mu} \leftrightarrow \nu_e$  oscillation is indeed observable

This will be the job for superbeams.

## NEUTRINO SUPERBEAMS

These beams are conventional neutrino beams, but obtained with the next generation of very high intensity proton drivers

These proton drivers are required for:

- neutrino factories
- Radioactive ion production
- Spallation source
- Nuclear waste burning
- hybrid reactors

Several projects worldwide

JAPAN : 50 GeV protons 0.8 MW  $\rightarrow$  4 MW

FNAL : NuMI 120 GeV p. 0.4 MW  $\rightarrow$  1.2 MW

CERN : SPL 2.2 GeV p 4 MW

Could ultimately allow to test for  $\theta_{13}$  down to  $1^\circ$ .

How? : Put a megaton detector at the right distance :  $L_{osc}^{atm} / 2$

# (High Intensity) Proton Accelerators

	Power (MW)	Energy (GeV)	Intensity ( $10^{12}$ ppp)	Rep. rate (Hz)
KEK-PS	0.005	12	6	0.45
AGS	0.14	24	60	0.6
FNAL-MI	0.41	120	40	0.53
SPS	0.3	400	35	0.16
JHF-I	0.77	50	330	0.29
Super-AGS	1.3	28	120	2.5
FNAL-proton driver-I	1.2	16	30	15
SPL	4	2.2	230	50
JHF-II	4	50		

■ Not the construction stage yet, but R&D stage.

## Back to $\nu_\mu \rightarrow \nu_e$ oscillation

- Let us suppose a monochromatic  $\gamma$  beam and a detector at the oscillation maximum.
- If  $E_\nu < 10 \text{ GeV}$ , no sizeable matter effects
- Then the oscillation formula simplifies greatly:

$$P_{\nu_e}(L_{\max}) = A^2 + S^2 \pm 2AS \sin \delta_{\nu, \bar{\nu}}$$

with  $A = \sqrt{2} F_{12}$  atmospheric term

$$S = c_{23} \sin 2\theta_{12} \sin \Delta_{12} t \approx 0.04$$

(notice that  $A = S$  for  $\theta_{13} \sim 1.6^\circ$ )

$\Rightarrow P_{\nu_e}$  is small, but CP asymmetry can be very large

(In 1<sup>st</sup> approximation, the sensitivity to  $\delta$  does not depend upon  $\theta_{13}$  value, as long as there are events ...)

# 3.1 JHF-Kamioka Neutrino Project

(hep-ex/0106019)

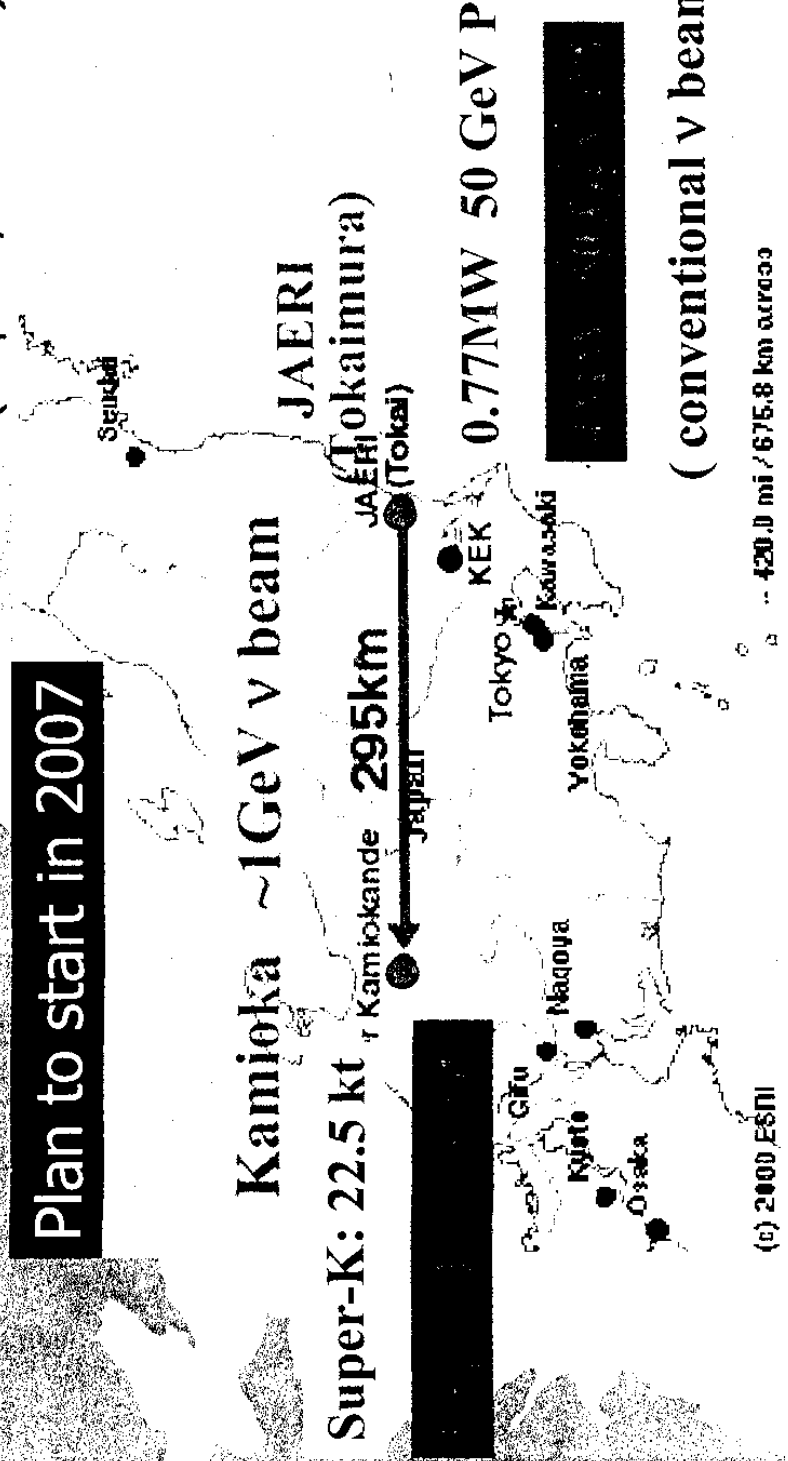
Plan to start in 2007

Kamioka ~1 GeV v beam

Super-K: 22.5 kt  
JAERI Tokaimura (Tokai)

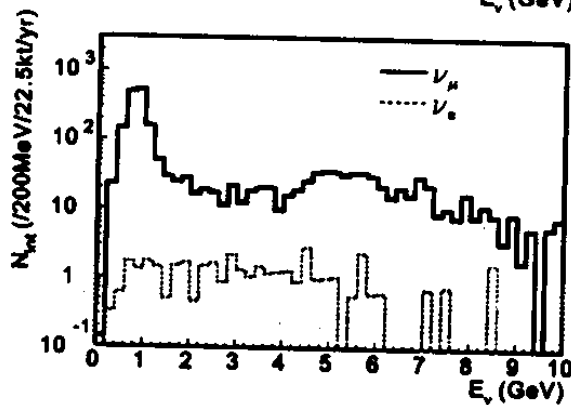
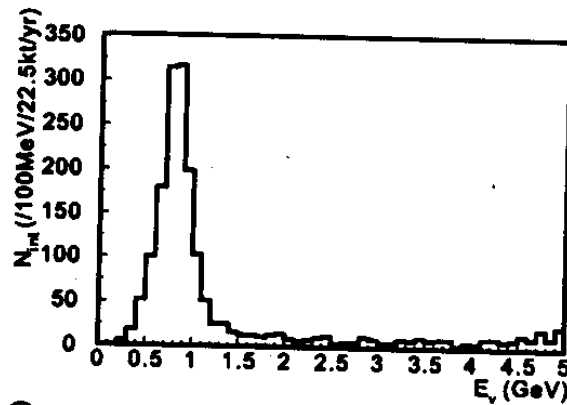
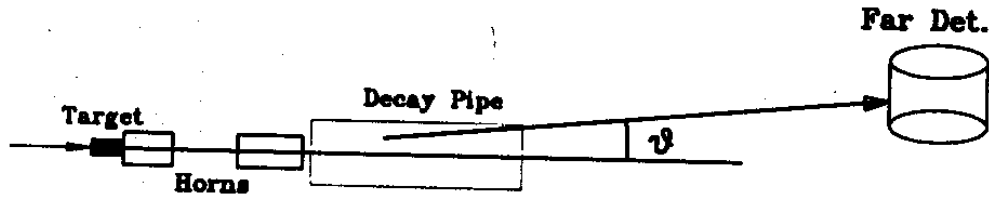
KEK 0.77MW 50 GeV PS

(conventional v beam)

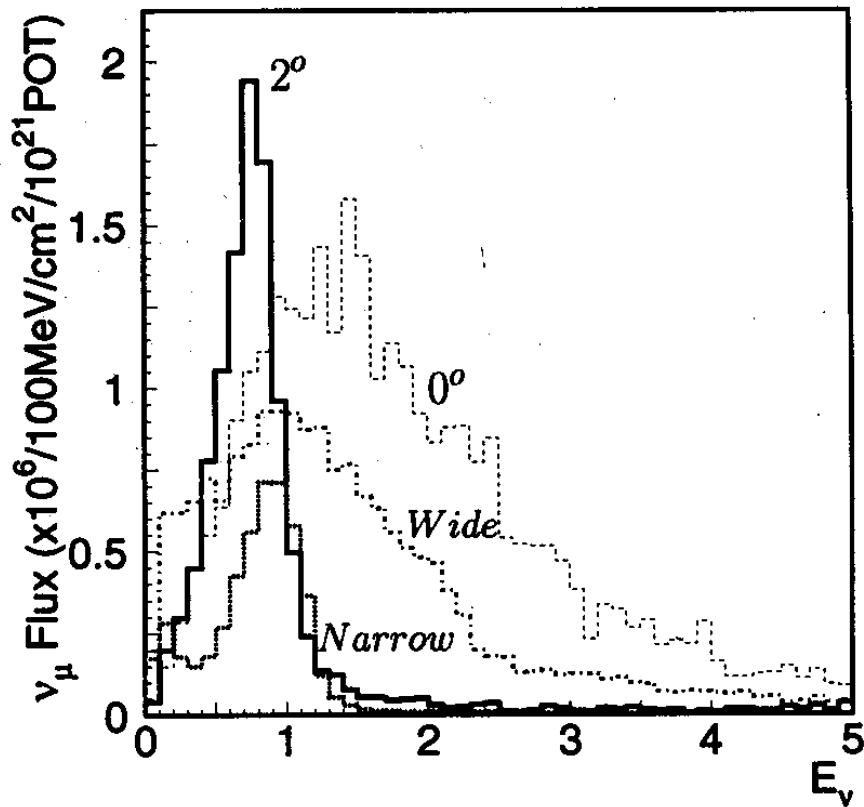


Phase-II (4MW+Hyper-K) ~  $\times 200$

## Off axis beam



- High intensity (2200 int./22kt/year)  
More than wide band at the peak energy
- Small backgrounds from high energy tail
- 0.2%  $\nu_e$  contamination (peak)
- Beam systematics under control  
Large oscillation signal



- Intensity of  $2^\circ$  off axis beam is higher than  $0^\circ$  wide band.

$$E_{max} = \frac{30 \text{ MeV}}{\theta \text{ (rad)}}$$

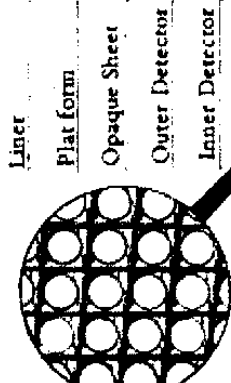
$$2^\circ \rightarrow E_{max} = 900 \text{ MeV}$$

$$3^\circ \quad \quad \quad 600 \text{ MeV}$$

# Hyper-Kamiokande (a far detector in the 2nd phase)

Good for atm.  $\nu$   
proton decay

~1,000 kt



Photomultipliers

Liner

Plat form

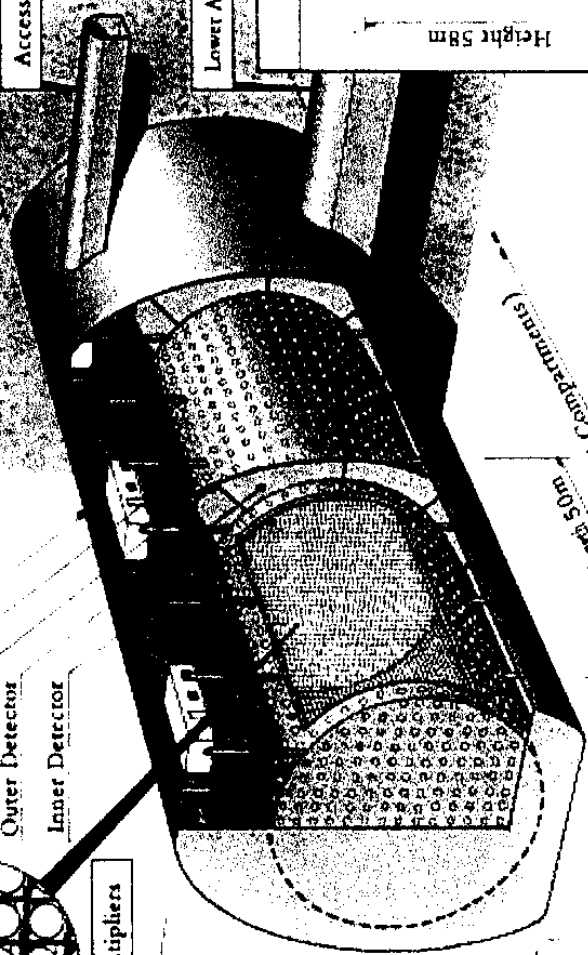
Opaque Sheet

Outer Detector

Inner Detector

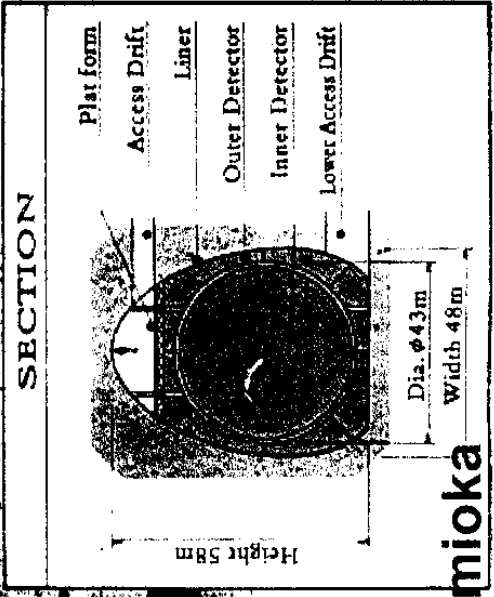
Access Drift

Lower Access Drift



General Length 50m  
(10 Compartments)  
Total Length 500m

Width 48m



Plat form

Access Drift

Liner

Outer Detector

Inner Detector

Lower Access Drift

Height 58m

Dia.  $\phi$  43m

Width 48m

Candidate site in Kamioka

# USA

1<sup>st</sup> stage (2008?)

Use NuMI beam (0.4 MW)

Build a fine grained calorimeter (~20 kT)  
at 700 km

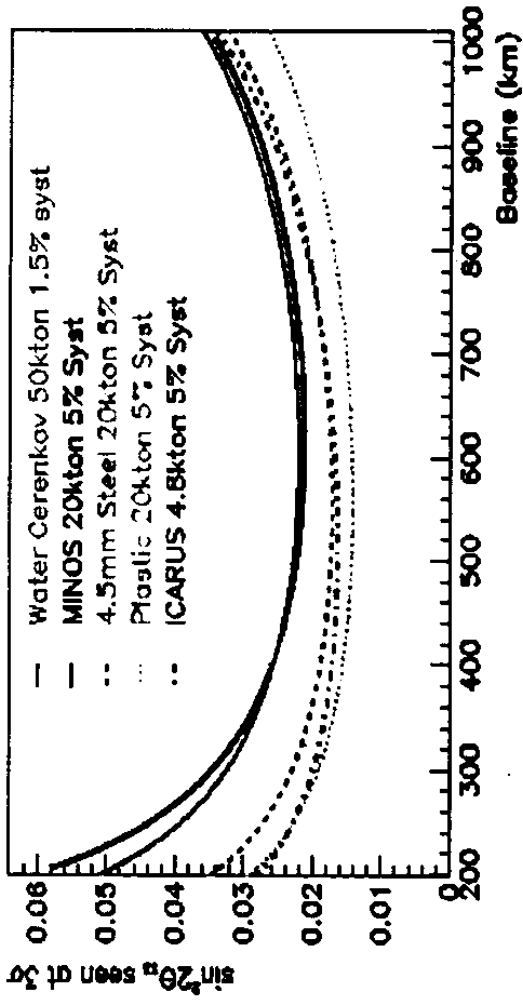
$\theta_{13}$  sensitivity 2 to 3°

2<sup>nd</sup> stage (date?)

either { BNL SuperAGS (1.3 MW)  
FNAL SuperNuMI (1.6 MW)

Detector { 100 kT liquid Argon  
660 kT WaterČ (UNO)

location: Soudan, Homestake, WIPP?

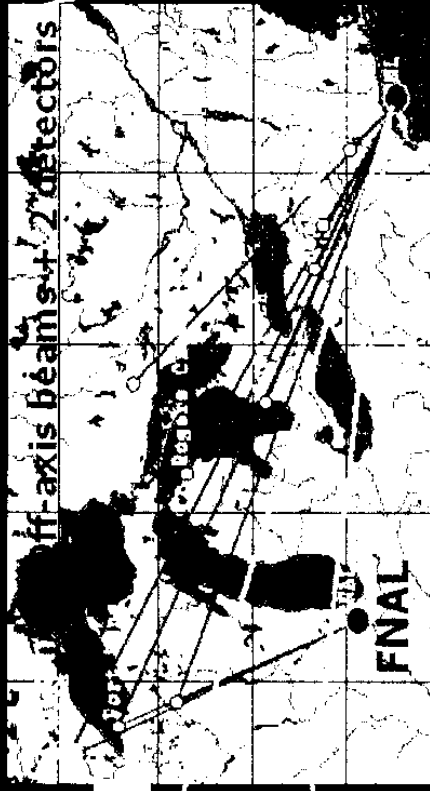


Detectors considered can see  $\sin^2 \theta_{13}$  at about 2 to 3%, which is a factor of 4 better than CHOOZ. But for the following assumptions:

- “Standards”: 20kton, 5% bkgd uncertainty
- $\Delta m_{23}^2 = 3.0 \times 10^{-3} eV^2$ ,  $\theta_{23} = 45^\circ$
- Liquid Argon needs 1/8th the “standard mass”
- Water Cerenkov needs 2.5 times the mass, 1/3 the syst. err

## 3.2 USA: FNAL and BNL plan

- BNL: Super AGS (1.3MW, LOI submitted)
- FNAL: Super NUMI (1.6 MW) or the new proton driver.



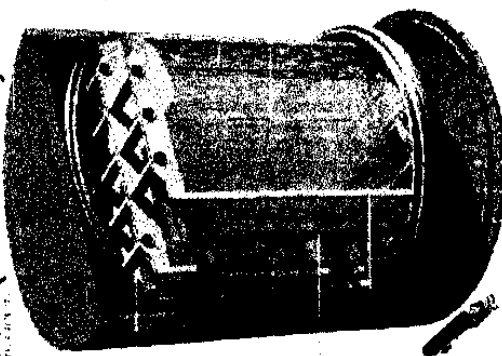
Homestake

WIPP

# Detectors

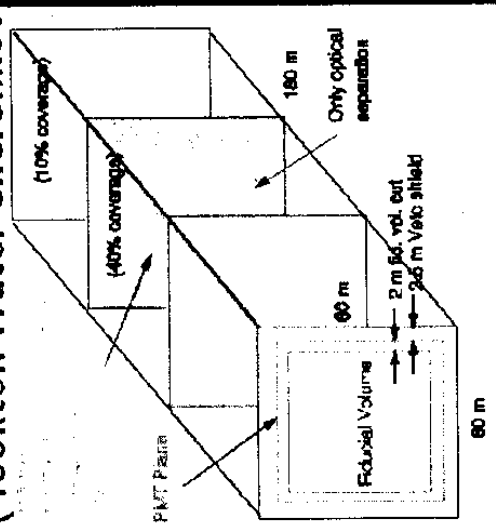
**Liquid Ar TPC  
(~100kton)**

1. Main detector
2. Outer veto
3. Inner veto
4. Support structure
5. Cryostat
6. Cryogenic system
7. Cryogenic piping
8. Cryogenic storage
9. Cryogenic monitoring
10. Cryogenic control



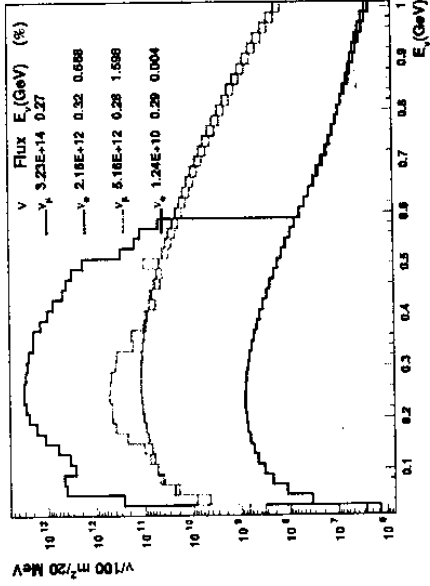
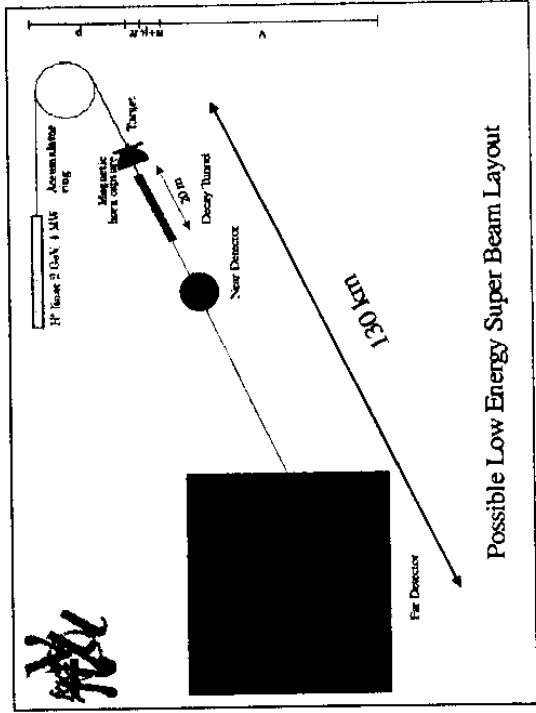
**LANDDO**  
Liquid Argon Neutron and Nuclear Cherenkov Detector

**UNO  
(400kton Water Cherenkov)**



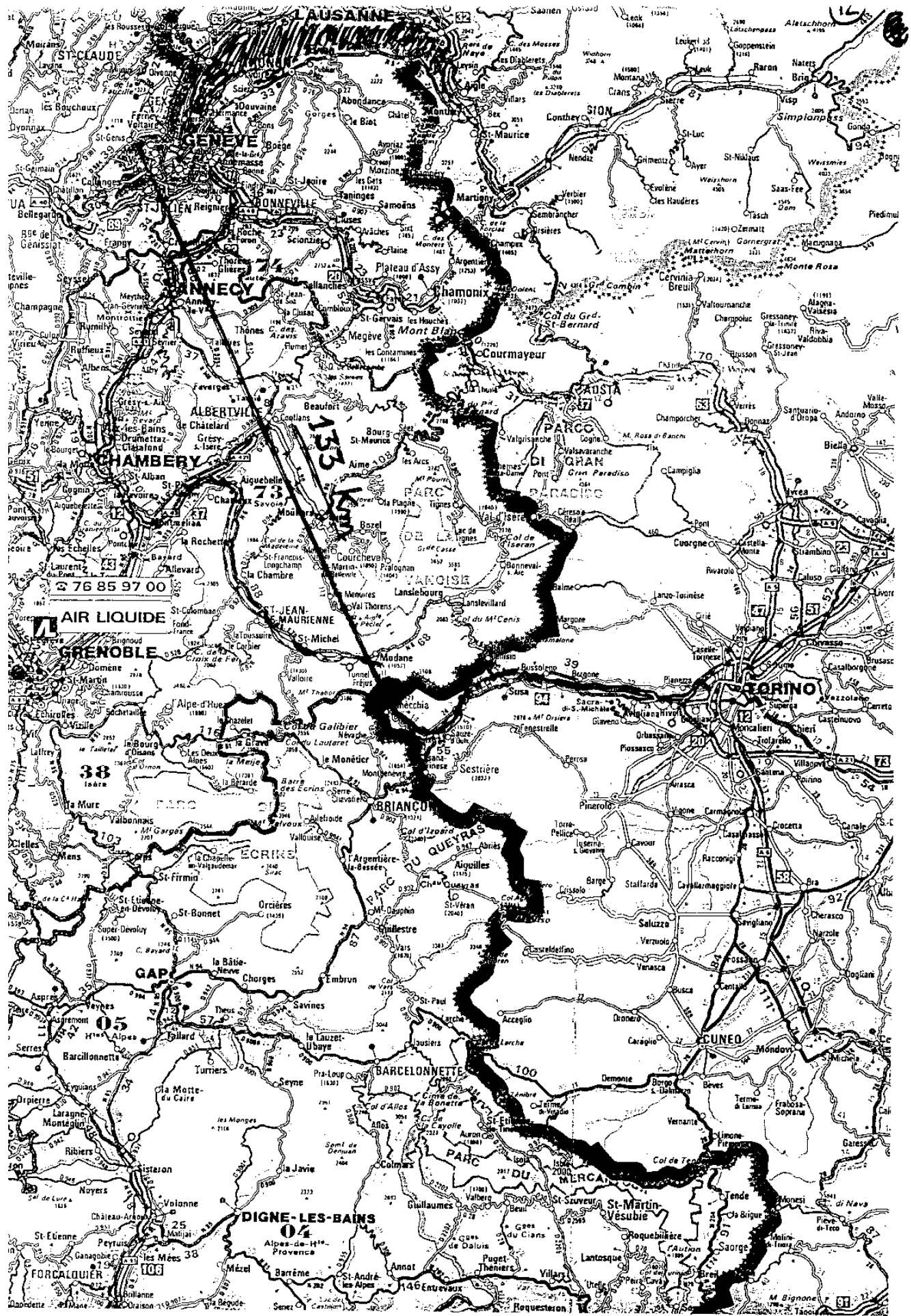
# SPL-SuperBeam at CERN

A feasibility study of the CERN possible developments



Flux Intensities at 50 km from the target

Flavour	Absolute Flux ( $\nu/10^{23}$ pot./m <sup>2</sup> )	Rel. Flux (%)	$E_{\nu}$ (GeV)
$\nu_{\mu}$	$3.2 \cdot 10^{12}$	100	0.27
$\nu_{\tau}$	$2.2 \cdot 10^{10}$	1.6	0.28
$\nu_e$	$5.2 \cdot 10^9$	0.67	0.32
$\bar{\nu}_e$	$1.1 \cdot 10^8$	0.004	0.29



76 85 97 00

AIR LIQUIDE

GRENOBLE

38

05

DIGNE-LES-BAINS

FORCALQUIER

135 KM

73

116

103

57

04

38

100

100

55

100

100

100

100

100

100

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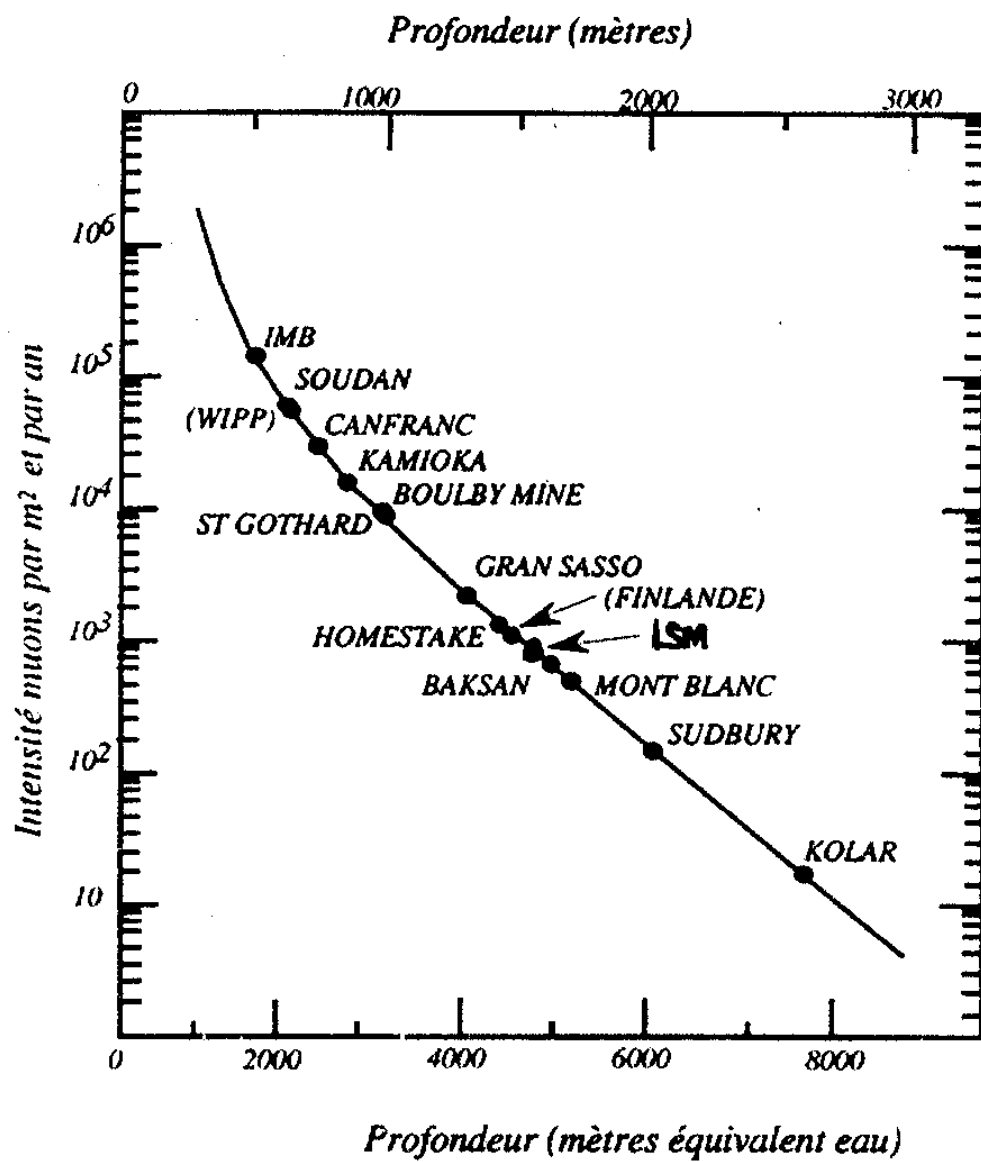
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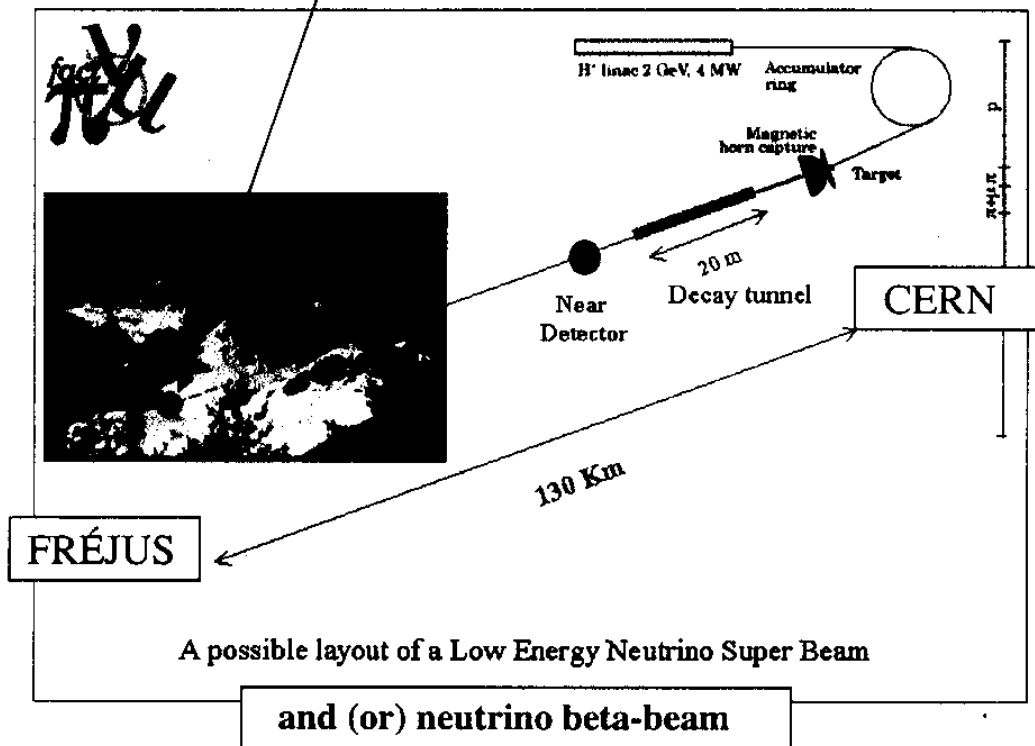
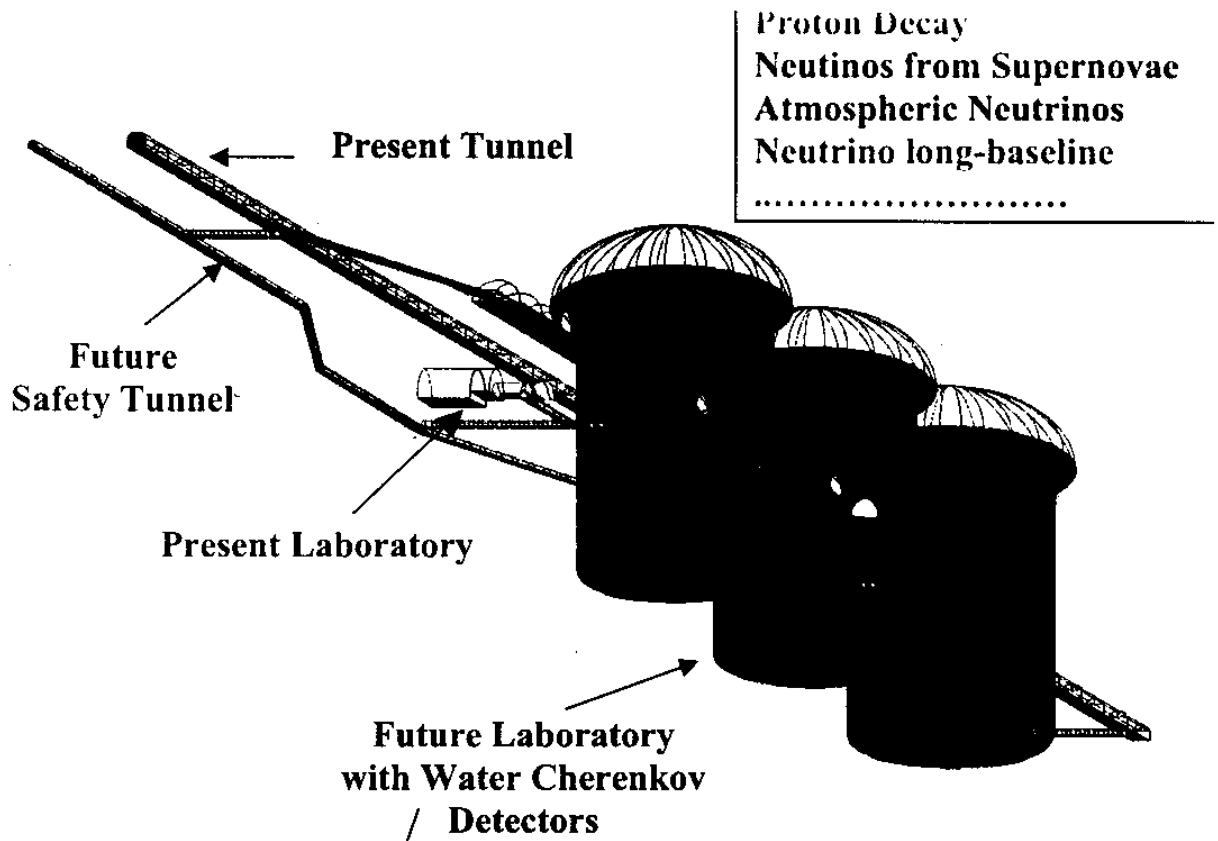
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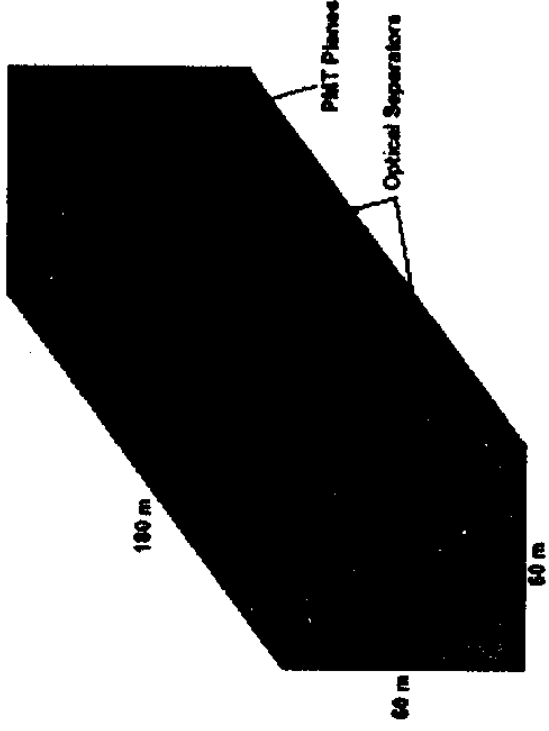
100

100





# A Baseline Design



- Total Mass: 648 kt
- Fiducial Mass: 440 kt
- Inner Region: ~ 60,000 20 inch PMTs
  - Considering 10-40% PMT coverage
- Outer Region: ~ 15000 8 inch PMTs

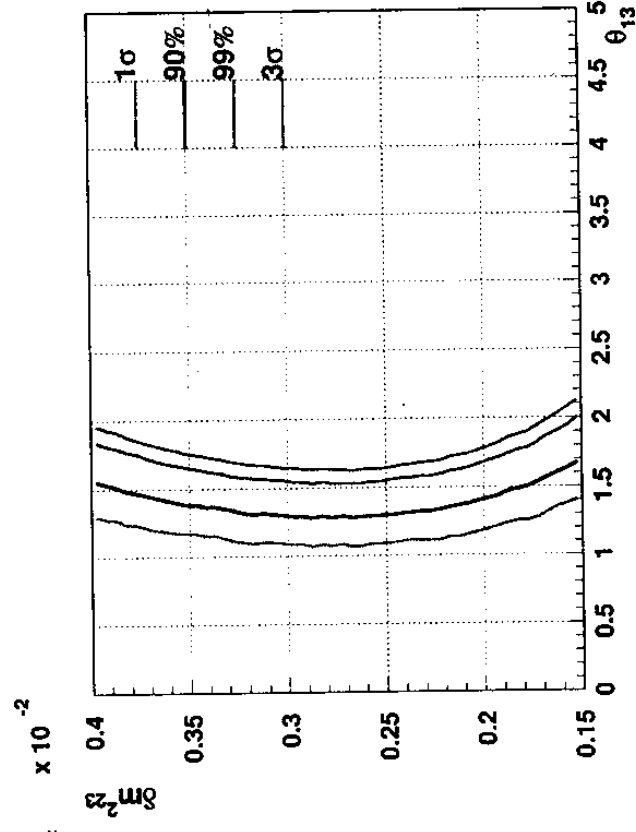
a point of comparison, not a final design

UNO

# Sensitivity to $\theta_{13}$ with a UNO like detector

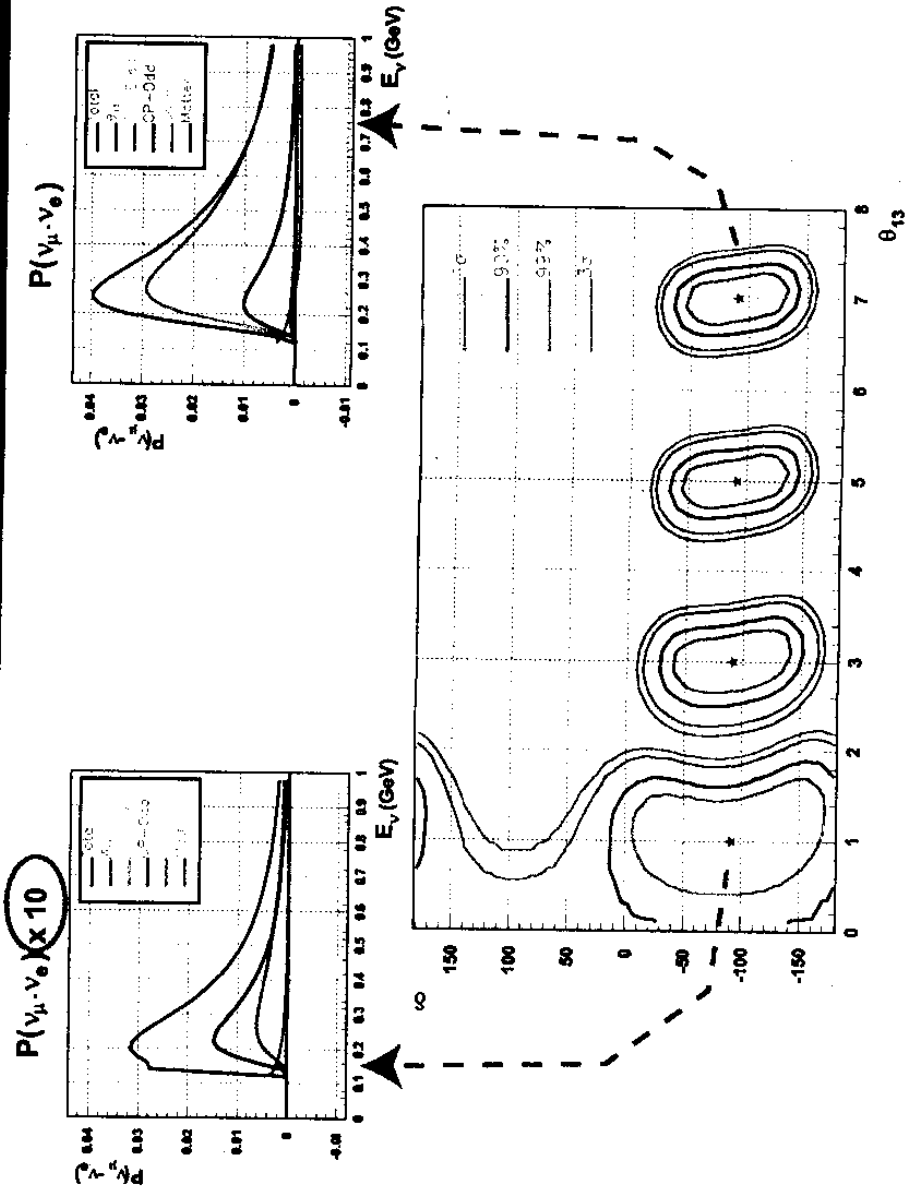
For the JHF limit:  $\sin^2 2\theta_{13} = 0.006$  ( $\delta m_{23}^2 = 2.5 \cdot 10^{-3} eV^2$ , solar SMA solution):

$\nu_{\mu}^{CC}$ (no osc.)	76782
Beam $\nu_e$	294
NC	153
$\mu/e$	71
<b>Signal</b>	<b>138 (<math>&gt; 5\sigma</math>)</b>



$\theta_{13}$  90%CL sensitivity:  $\theta_{13} = 1.2^\circ$   
 JHF 90%CL sensitivity:  $\theta_{13} = 2.3^\circ$   
 (Factor 3.7 better on  $\sin^2 2\theta_{13}$ )

$\delta$  and  $\theta_{13}$  interplay:  $P(\nu_\mu \rightarrow \nu_e) \propto \sin^2 2\theta_{13}$      $A_{CP} = \frac{N(e^-) - N(e^+)}{N(e^-) + N(e^+)} \propto \frac{1}{\sin\theta_{13}}$



# How to overcome superbearm limitations ?

Main problem :

SPL protons produce less negative pions, so less antineutrinos  
antineutrino cross-section  $\sim 5$  times smaller than neutrinos  
So 10 SPL years have to be shared as  $\sim 2$  neutrino + 8 antineutrino years

The solution :

Produce a  $\nu_e$  beam to study  $\nu_e \rightarrow \nu_\mu$  oscillation and run it SIMULTANEOUSLY with  $\nu_\mu$  beam from SPL

Compare  $\nu_\mu \rightarrow \nu_e$  and  $\nu_e \rightarrow \nu_\mu$  (T asymetry, equivalent to CP asymetry)

THIS WAS THE INITIAL MOTIVATION FOR A BETA BEAM

# BETA BEAMS

Concept proposed by Piero Zucchelli

- Produce radioactive ions (ISOL technique)
- Accelerate them in the CERN accelerator complex up to  $\Gamma$  of order 100
- Store ions in a storage ring with long straight sections aimed at a far detector

Advantages

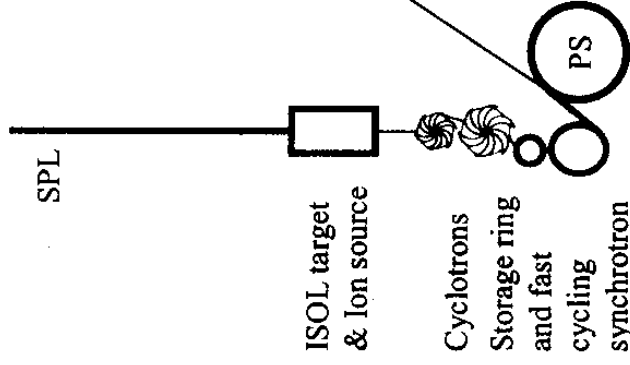
- strongly focussed neutrino beam due to small  $Q$  value of beta decays (quality factor  $\Gamma/Q$ )
- very pure flavour composition ( $\nu_\mu$  contamination  $\sim 10^{-4}$ )
- perfectly known energy spectrum

Baseline scenario studied at CERN (Mats Lindroos and collaborators)

Recent progress presented at a special workshop at Moriond  
Possible synergy between beta beams and EURISOL

Updated study of expected performances (Mauro Mezzetto)

# $\beta$ -beam initial baseline scenario (before Moriond)



**Decay ring**

Brho = 1500 Tm

B = 5 T

$L_{ss} = 2500$  m

${}^6_2\text{He} \rightarrow {}^6_3\text{Li} e^- \bar{\nu}$

Average  $E_{\text{ems}} = 1.937$  MeV

${}^{18}_{10}\text{Ne} \rightarrow {}^{18}_9\text{Fe} e^+ \nu$

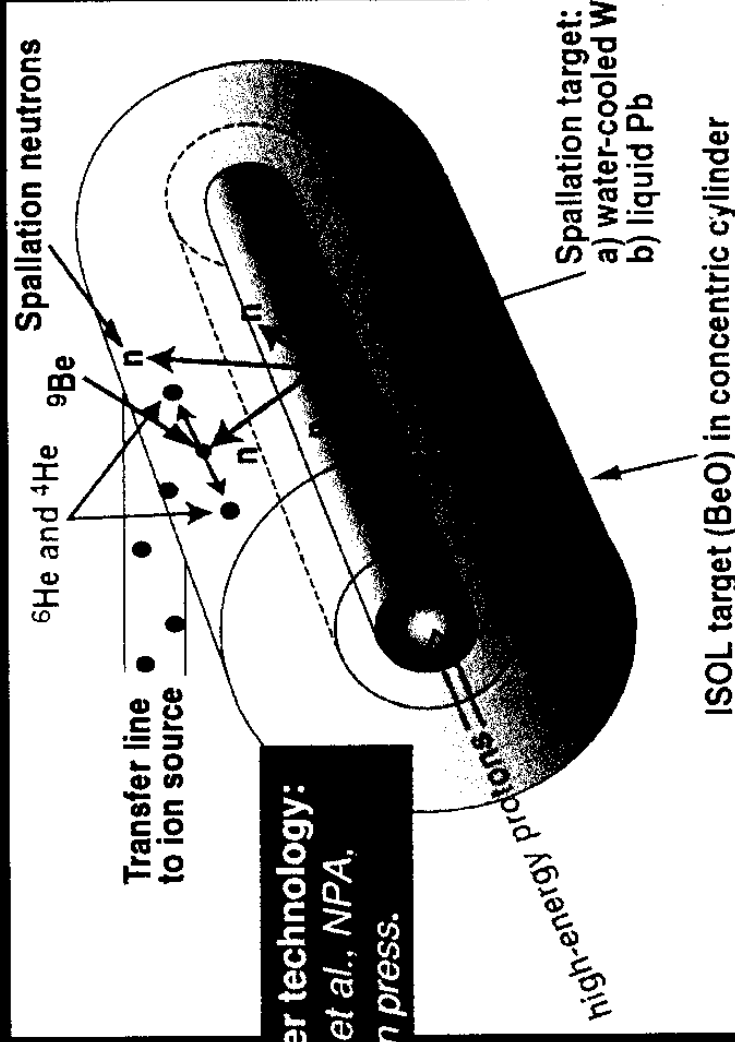
Average  $E_{\text{ems}} = 1.86$  MeV

# B

## Possible $\beta^-$ emitters ( $\bar{\nu}_e$ )

Isotope	Z	A	Z	$T_{1/2}$ s	$Q_{\beta}^{\text{eff}}$ MeV	$Q_{\beta}^{\text{eff}}$ MeV	$E_{\beta}^{\text{max}}$ MeV	$E_{\beta}^{\text{av.}}$ MeV	$\langle E_{\text{LAB}} \rangle$ (@ 450 GeV/p)
6He	2	6	3.0	0.807	3.5	3.5	1.57	1.94	582
8He	2	8	4.0	0.069	10.7	9.1	4.35	4.80	1079
8Li	3	8	2.7	0.838	16.0	13.0	6.24		2268
9Li	3	9	3.0	0.178	13.6	11.9	5.73	6.20	1860
11Be	4	11	2.8	13.81	11.5	9.8	4.65	5.11	1671
15C	6	15	2.5	2.449	9.8	6.4	2.87	3.55	1279
16C	6	16	2.7	0.747	8.0	4.5	2.05	2.46	830
16N	7	16	2.3	7.13	10.4	5.9	4.59	1.83	525
17N	7	17	2.4	4.173	8.7	3.8	1.71	2.10	779
18N	7	18	2.6	0.624	13.9	8.0	5.33	2.67	933
23Ne	10	23	2.3		4.4	4.2	1.90	2.31	904
25Ne	10	25	2.5	0.602	7.3	6.9	3.18	3.73	1344
25Na	11	25	2.3	59.1	3.8	3.4	1.51	1.90	750
26Na	11	26	2.4	1.072	9.3	7.2	3.34	3.81	1450

9118 010118 4400 by 9730/n/a



**Converter technology:**  
J. Nolen et al., NPA,  
RNB-5, in press.

**U. Köster, EP-ISOLDE**

# The Anti-Neutrino Source

Consider  ${}^6\text{He}^{++} \rightarrow {}^6\text{Li}^{+++} + \bar{\nu}_e e^-$

$Q = 3.5078 \text{ MeV}$   $T/2 \approx 0.8067 \text{ s}$

1. The ion is spinless, and therefore decays at rest are isotropic.

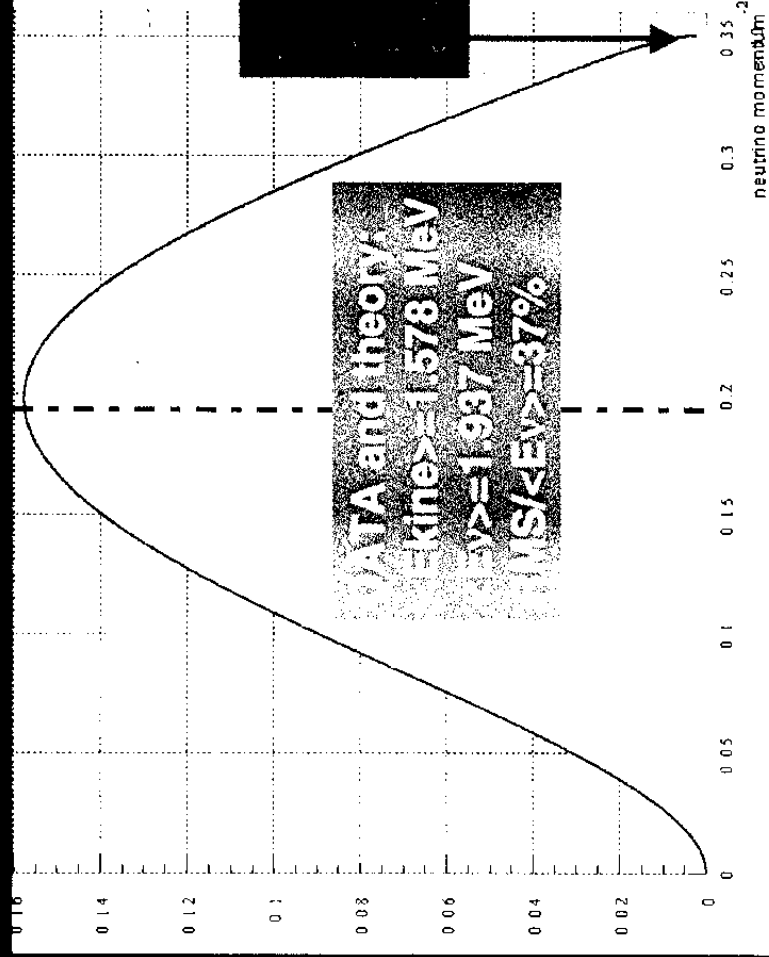
2. It can be produced at high rates

3. The neutrino spectrum is known on the basis of the electron spectrum.

B.M. Rustand and S.L. Ruby, Phys. Rev. 97 (1955) 991  
B.W. Fidley Nucl. Phys. 25 (1961) 483

806.7 ms  
 $0^{++}, T=1$   
 ${}^6\text{He}$   
 $Q_{\beta^-} = 3507.8$

100%  $2.9$   $1^{++}, T=0$   $0$  stable  
 ${}^6\text{Li}$



# The Far Detector Background

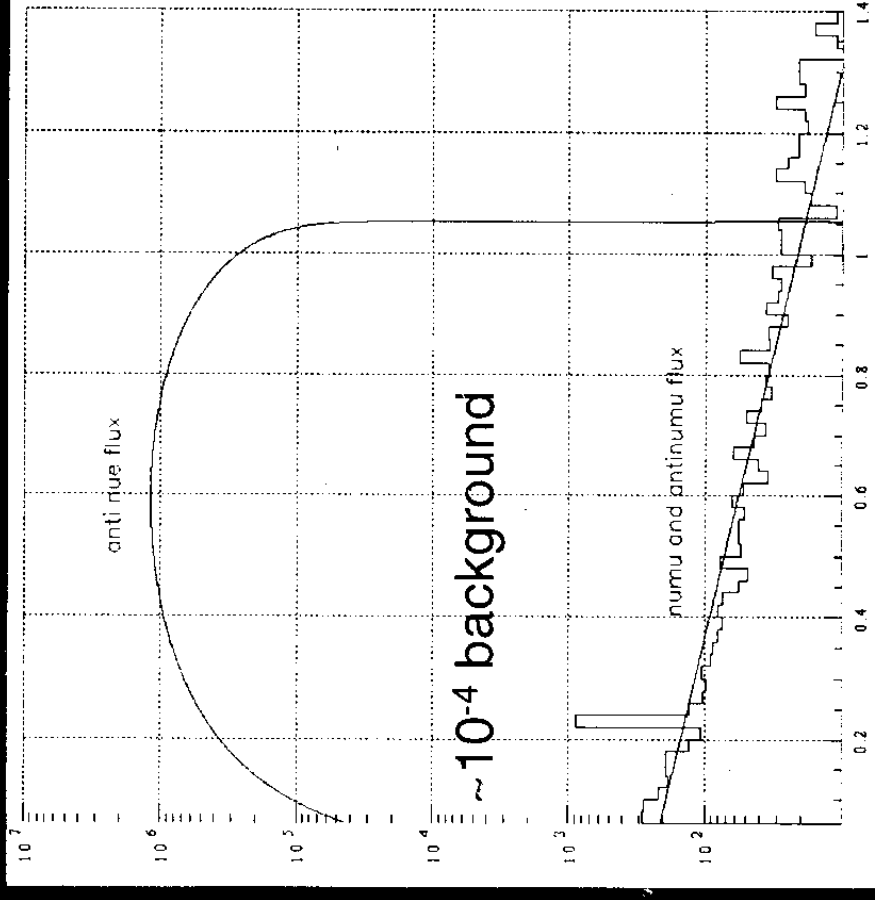
beam-related backgrounds  
due to Lithium  
interactions at the  
end of the straight  
sections

GEANT3 simulation,

3E6 proton  
interactions  
onto a Fe dump,

tracking down to 10 MeV

100 mrad  
off-axis and  
130 km distance.  
DIF and DAR  
(K+) contributions





# Possible $\beta^+$ emitters ( $\nu_e$ )

Isotope	Z	A	A/Z	$T_{1/2}$ s	$Q_{\beta}^{(gs \rightarrow gs)}$ MeV	$Q_{\beta}^{eff.}$ MeV	$E_{\beta}^{av.}$ MeV	$E_{\nu}^{av.}$ MeV	$\langle E_{LAB} \rangle$ (MeV) (@450 GeV/p)
8B	5	8	1.6	0.77	17.0	13.9	6.55		4145
10C	6	10	1.7	19.3	2.6	1.9	0.81	1.08	585
14O	8	14	1.8	70.6	4.1	1.8	0.78	1.05	538
15O	8	15	1.9		1.7	1.7	0.74	1.00	479
18Ne	10	18	1.8	1.67	3.4	3.4	1.50	1.86	930
19Ne	10	19	1.9	17.34	2.2	2.2	0.96	1.25	594
21Na	11	21	1.9	22.49	2.5	2.5	1.10	1.41	662
33Ar	18	33	1.8	0.173	10.6	8.2	3.97	4.19	2058
34Ar	18	34	1.9	0.845	5.0	5.0	2.29	2.67	1270
35Ar	18	35	1.9	1.775	4.9	4.9	2.27	2.65	1227
37K	19	37	1.9	1.226	5.1	5.1	2.35	2.72	1259
80Rb	37	80	2.2	34	4.7	4.5	2.04	2.48	1031

# A VERY EXCITING POSSIBILITY

Nothing forbids to store at the same time  $^{18}\text{Ne}$  and  $^6\text{He}$  ions in the decay ring with no loss of intensity for each species

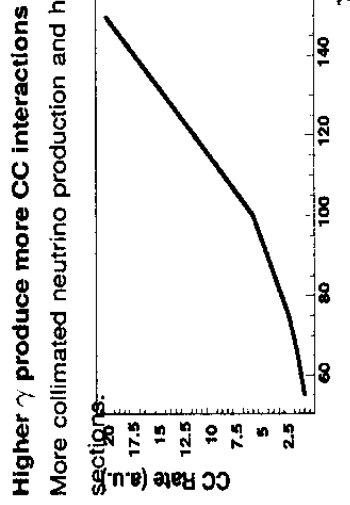
But as the rigidities for Neon and Helium will be different, the neutrino and antineutrino energies will be in the ratio 5 to 3.

First studies show that this energy difference is quite acceptable

This brings immediately a gain of a factor nearly 2 in run time to achieve a given sensitivity on CP violation with beta beams

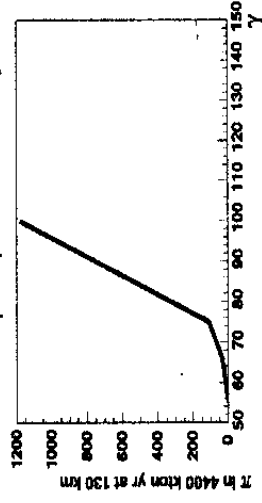
# Lorentz boost optimization : Preferred values $\gamma = 55$ and $75$

## Optimizing the Lorentz Boost (L=130 km): preferred values: $\gamma = 55$ and $75$

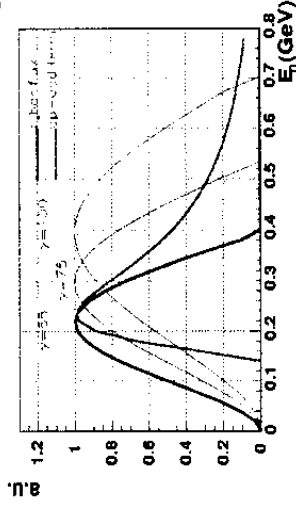


Background rate rises much faster than CC interactions

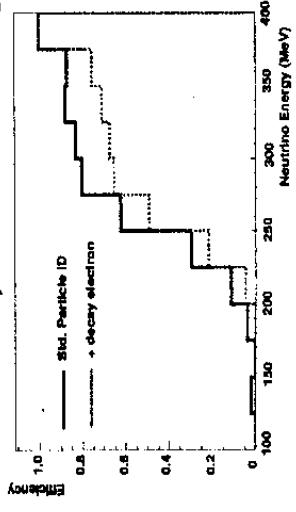
From resonant pion production in  $\bar{\nu}_e$  NC interactions



$\nu$  flux must match the CP-odd oscillating term



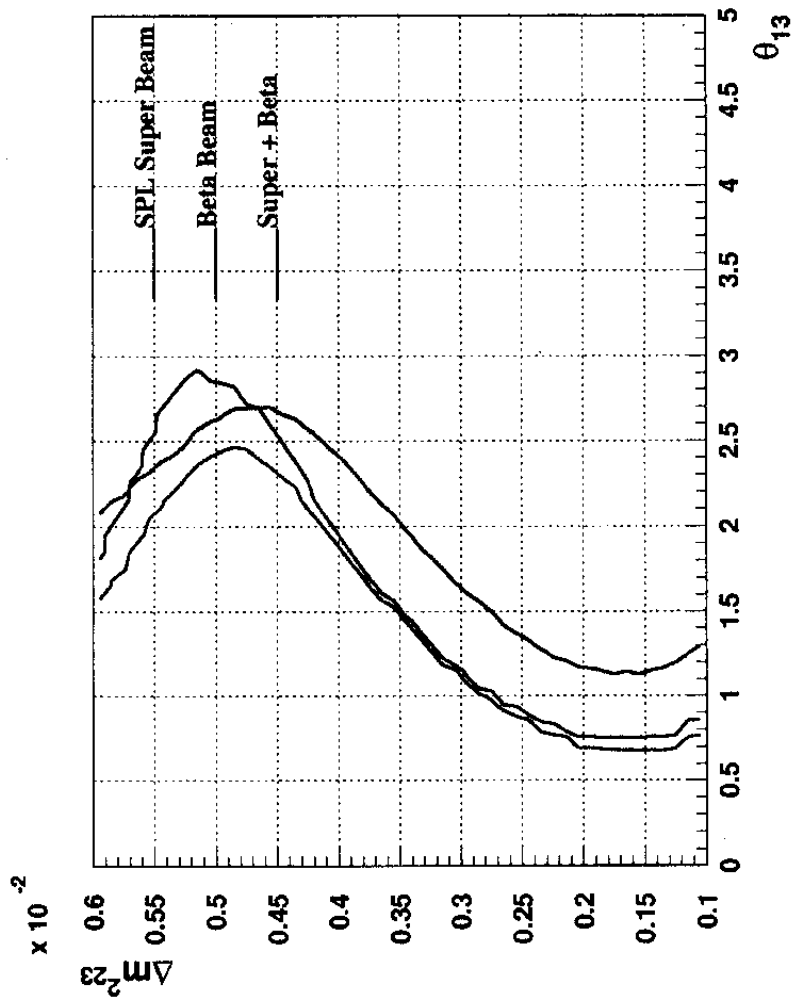
Detection efficiency as function of  $\nu$  energy



## Beta Beam - Super Beam synergy: $\theta_{13}$ sensitivity

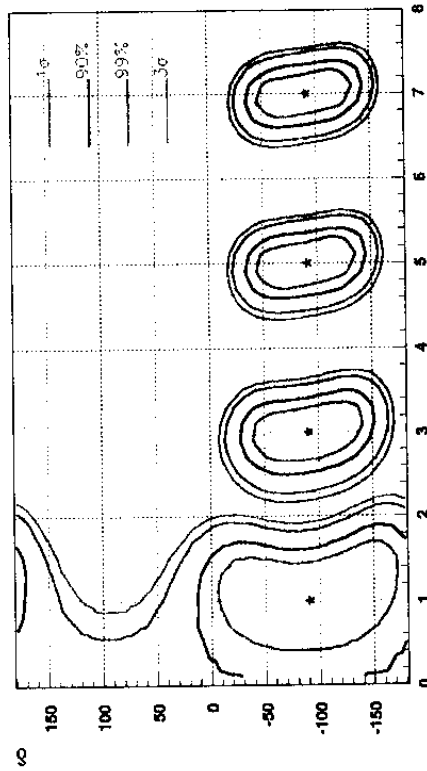
Computed for  $\delta_{CP} = 0$  (standard benchmark)

- Super Beam  $\rightarrow 68 \times$  CHOOZ.
- Super Beam + Beta Beam  $\rightarrow 230 \times$  CHOOZ.

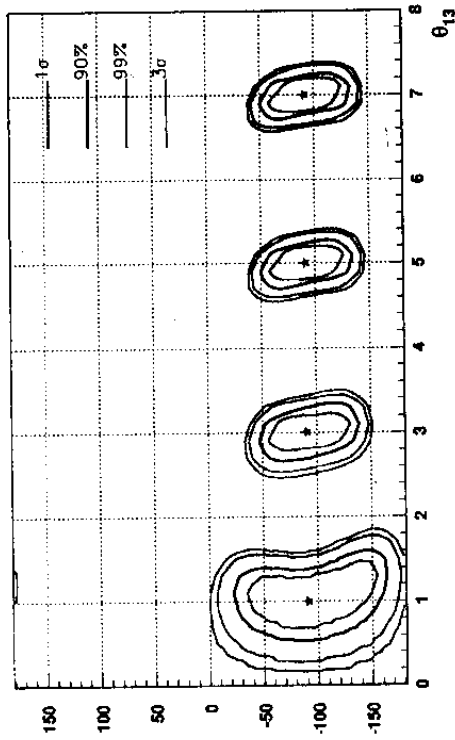


# $\theta_{13}$ and $\delta$ measurements using superbeam and betabeam

**SUPER BEAM ONLY**



**SUPER BEAM + BETA BEAM**



$$\delta m_{12}^2 = 7 \cdot 10^{-5} \text{ eV}^2, \theta_{13} = 4^\circ, \delta_{CP} = -\pi/2$$

10 yrs (4400 kton/yr)	SuperBeam		Beta Beam	
	$\nu_\mu$	$\bar{\nu}_\mu$	$\nu_e$ (He <sup>6</sup> )	$\bar{\nu}_e$ (Ne <sup>18</sup> )
	(2 yrs)	(8 yrs)	$\gamma = 60$	$\gamma = 96$
CC events (no osc, no cut)	36698	23320	28880	140073
Total oscillated	314	67	147	168
CP-Odd oscillated	102	-64	47	-132
Beam background	141	113	/	/
Detector bkg.	37	50	1	299

**SPL:**

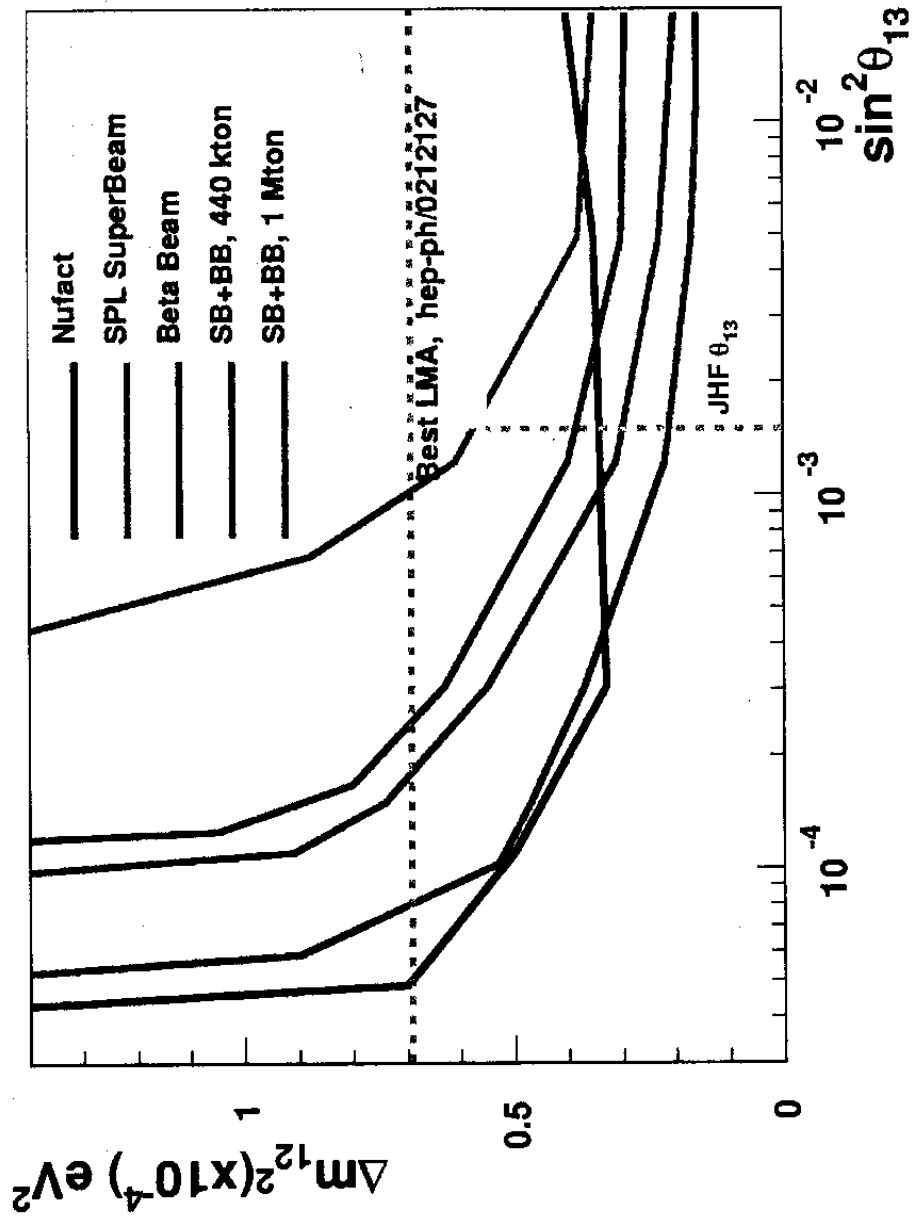
2 years in  $\nu_\mu$  + 8 years in anti  $\nu_\mu$

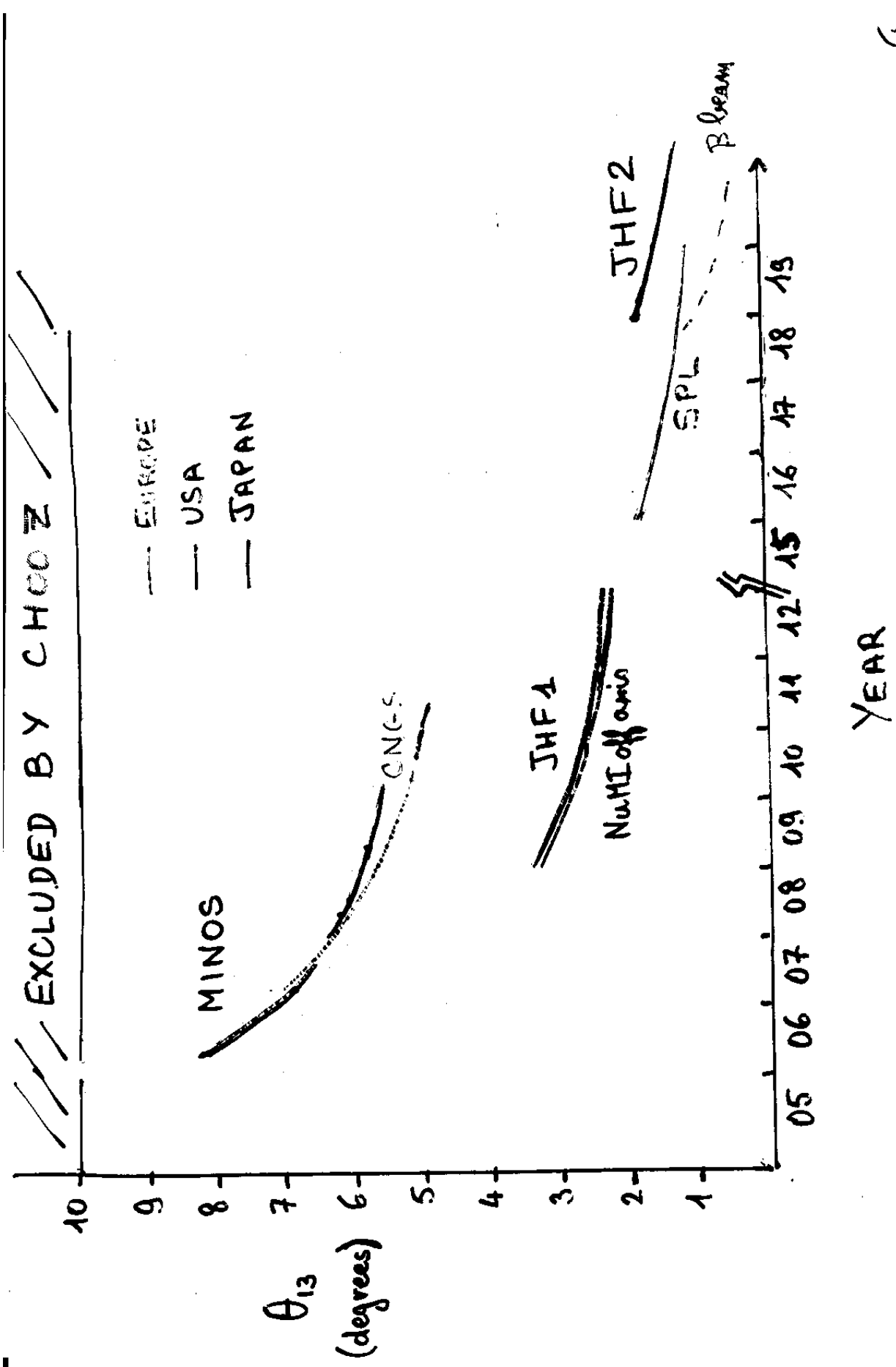
**BETABEAM:**

10 years of <sup>6</sup>He AND <sup>18</sup>Ne  
(Mauro Mezzetto)

# CP sensitivity :

domain of 99% CL effect for maximal CP violation





## A STRATEGY FOR EUROPE

(34)

- Dig a  $10^6 \text{ m}^3$  cavity and install a UNO-like detector (UNO itself welcome!)
- Start "megaton physics" in 2015 (p decay, Solar/Atm  $\nu$ , Supernovae)  
 $\Rightarrow$  cf. Dave Casper's talk yesterday
- When SPL comes in, study  $\nu_\mu \leftrightarrow \nu_e$  osc. with a  $\theta_{13}$  sensitivity around  $1^\circ$  and perform  $\bar{\nu}\nu$  searches
- If CERN builds a  $\beta$ -beam, added performances on  $\delta$  phase.

# Nucleon Decay Sensitivity

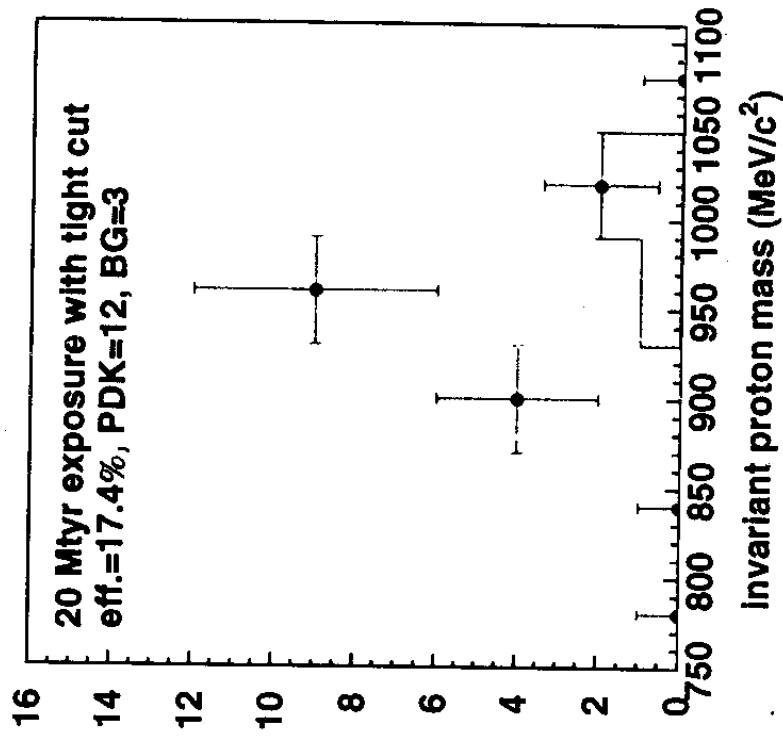
Mode	Super-Kamiokande		UNO	
	Current	After 10 yr	5 yr	15 yr
$p \rightarrow e^+ \pi^0$	$5 \times 10^{33}$ yr	$3 \times 10^{34}$ yr	$6 \times 10^{34}$ yr	$2 \times 10^{35}$ yr
$p \rightarrow \nu K^+$	$1.6 \times 10^{33}$ yr	$5 \times 10^{33}$ yr	$1 \times 10^{34}$ yr	$2 \times 10^{34}$ yr

Background estimation is important. The K2K experiment is currently collecting a  $\sim 20$  M<sub>tyr</sub> equivalent exposure.

*Découverte possible si SUSY GUT*

*Fenêtre sur l'échelle de grande unification*

# $p \rightarrow e^+ \pi^0$ Signature



- $p \rightarrow e^+ \pi^0$
- Optimized for free protons
  - $P_{tot} < 100$  MeV
  - $\tau = 1 \times 10^{35}$  yr

A clear discovery signal

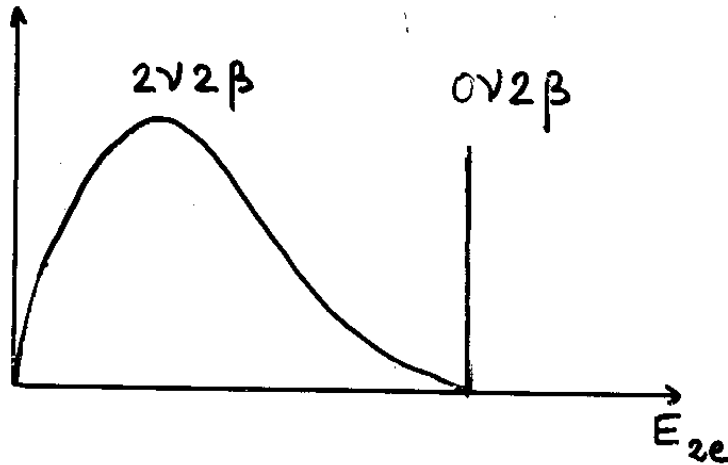
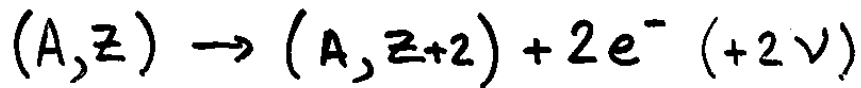
# UNO and Supernova Neutrinos

A Supernova at 10 kpc

Detector	Method	Mass	Events
UNO	water Cherenkov	400 kt	140,000
Super-Kamiokande	water Cherenkov	22.5 kt	9,000
OMNIS	neutron capture	several kt	~2,000
SNO	water Cherenkov	1 kt	1,000
KamLAND	scintillation	1 kt	~500
Borexino	scintillation	1 kt	~500
LVD	scintillation	0.5 kt	~200

- Estimate  $3 \pm 1$  Supernova per century in our galaxy (Beacom et al. PRD63,073011).
- UNO would detect ~10 events for a supernova in Andromeda.

# NEUTRINOLESS DOUBLE BETA DECAY



$$T_{1/2}^{-1}(0\nu) \propto |m_{\text{eff}}|^2 |M_{\text{NUCL}}|^2$$

$$\sum_i U_{ei}^2 m_i$$

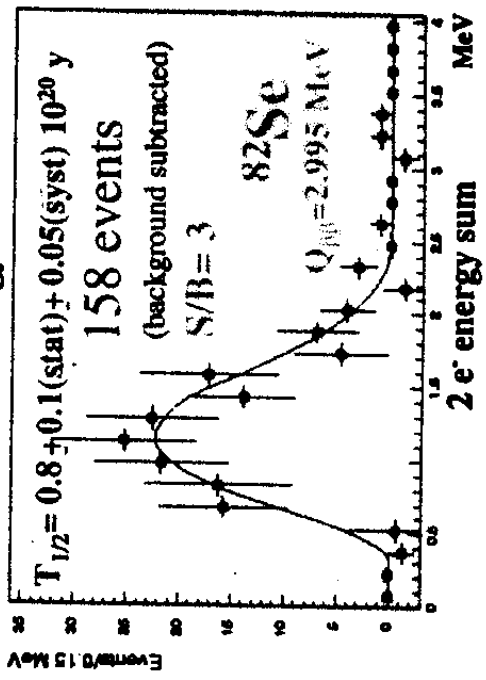
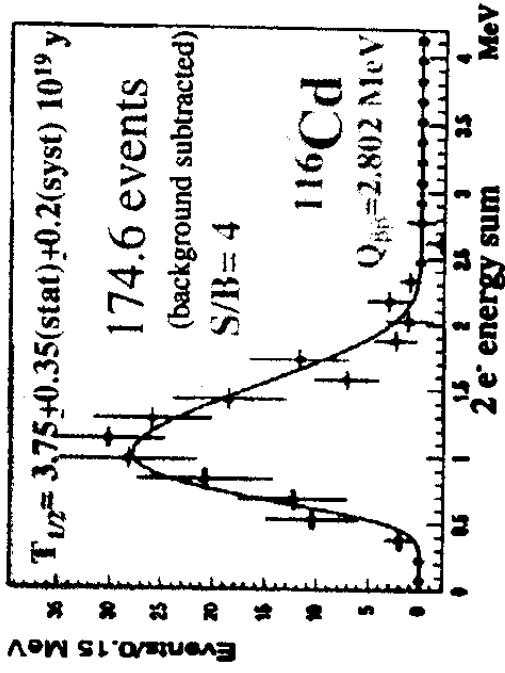
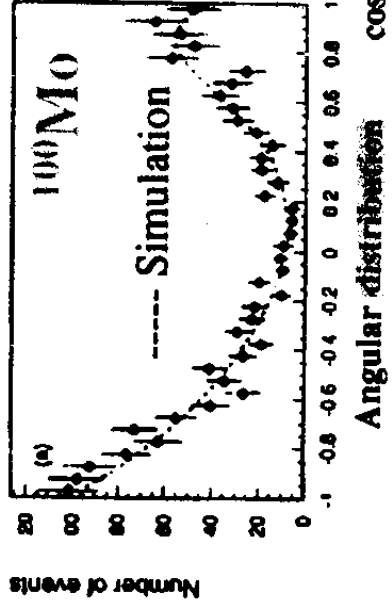
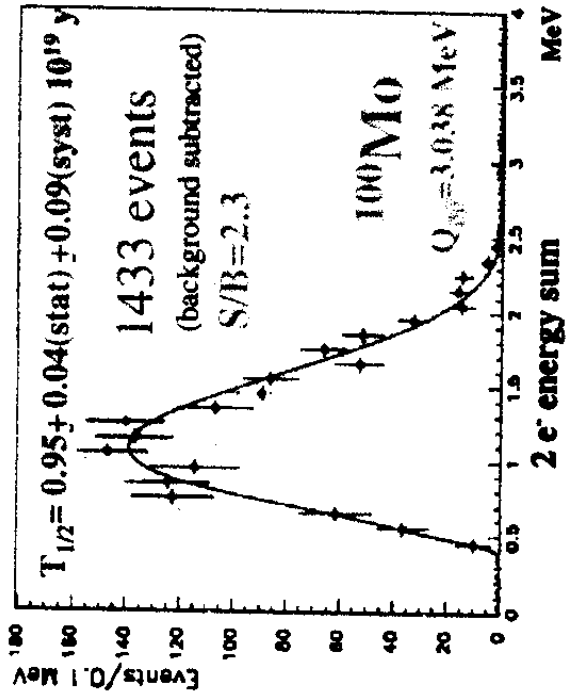
[Possible cancellations]

Progress needed  
on computation  
(observation of  $2\nu 2\beta$  helps)

Sensitivity to low  $m_{\text{eff}}$  requires:

- 1) Very low background
- 2) Good energy resolution ( $2\nu 2\beta$  ultimate backgd.)
- 3) High masses of  $(A, Z)$  isotope

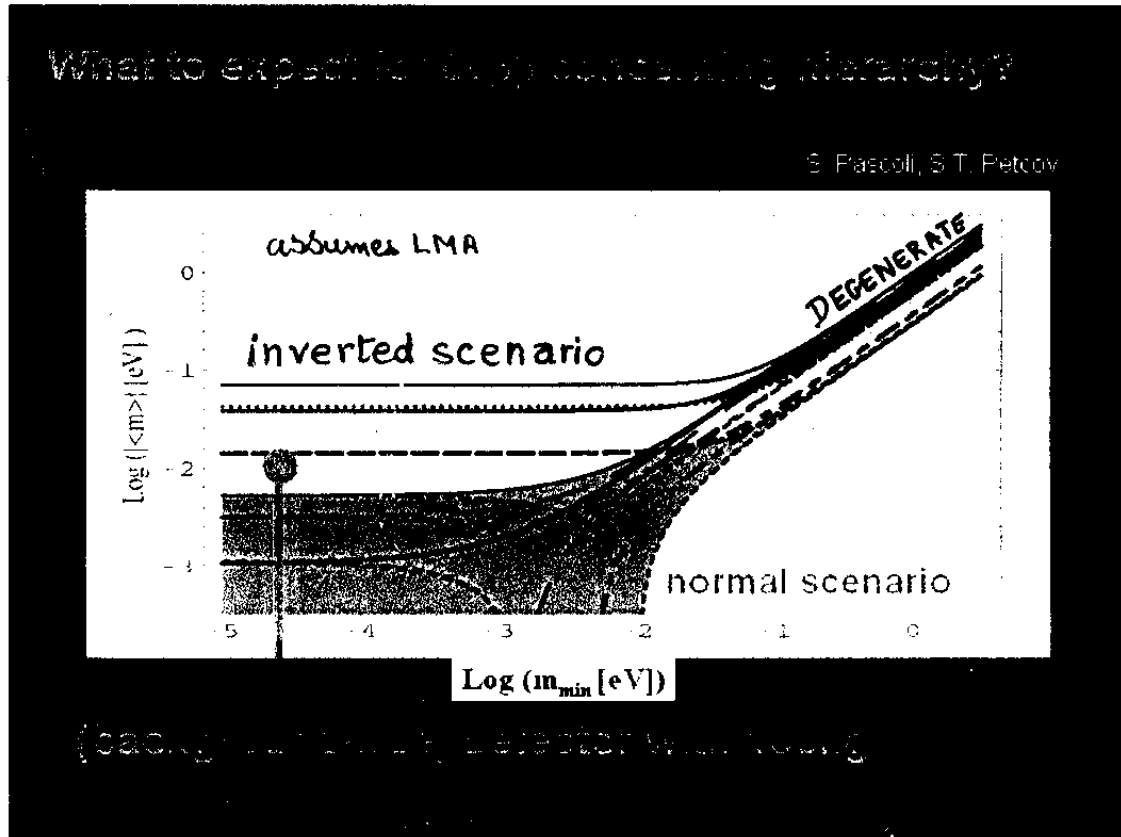
# NEMO 2 $\beta\beta(2\nu)$ RESULTS



$^{96}\text{Zr}$   $T_{1/2} = 2.1^{+0.8}_{-0.4} \pm 0.2(\text{syst}) 10^{19} \text{ y}$   
 $Q_{\beta\beta} = 3.350 \text{ MeV}$

$$A_{\nu\gamma\beta\beta} \propto m_{\text{eff}} = \sum_i U_{ei}^2 m_i$$

↳ complex (Majorana phases)



Bands created by Majorana phases (CP violation)

A positive signal:

→ would prove that  $\nu$ 's are Majorana

→ would give  $m_{\text{eff}}$

→ might determine the mass hierarchy



# Heidelberg-Moscow

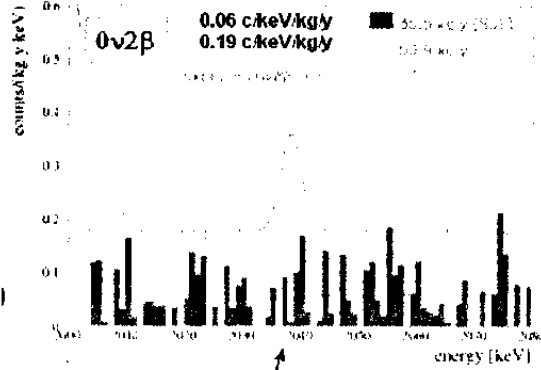
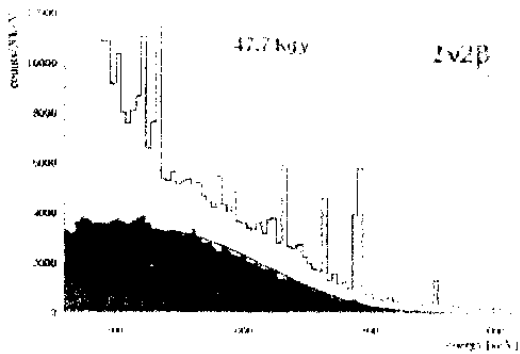
Klapdor-Kleingrothaus HV et al. Eur. Phys. J. 12 (2001) 147

Max-Planck-Institut für Kernphysik  
Russian Science Center Kurchatov Institute

since 1990

Gran Sasso underground laboratory

- Five Ge diodes (overall mass 10.9 kg) isotopically enriched (86%) in  $^{76}\text{Ge}$
- Lead box and nitrogen flushing of the detectors
- Digital Pulse Shape Analysis (factor 5 reduction)



$$T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ (90 \% C.L.)}$$

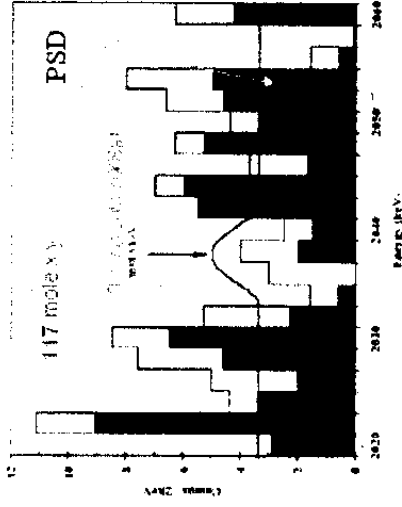
$$\langle m_{\nu} \rangle < 0.35 \text{ (0.3-1.24) eV}$$

Accurate background model:

$$T_{1/2}^{2\nu} > (1.55 \pm 0.01(\text{stat}) +0.13_{-0.15}(\text{syst})) \times 10^{21}$$

# IGEX

Pacific Northwest National Laboratory (PNNL)  
 University of South Carolina (USC)  
 Institute for Theor and Exp Physics (ITEP, Russia)  
 Institute for Nuclear Research (INR, Russia)  
 Yerevan Physical Institute (Armenia)  
 University of Zaragoza (UZ)



$$T_{1/2}(0\nu,0^+\rightarrow0^+) > 1.57 \times 10^{25} \text{ y (90\%)}$$

$$\epsilon m_\nu \leq 0.33\text{--}1.35 \text{ eV}$$

1994-2000

Cambrian underground laboratory  
 (Laboratory 3 at 2450 m.w.e.)

Three (2kg) Ge diodes (86% <sup>76</sup>Ge)

**FWHM: 4 keV**

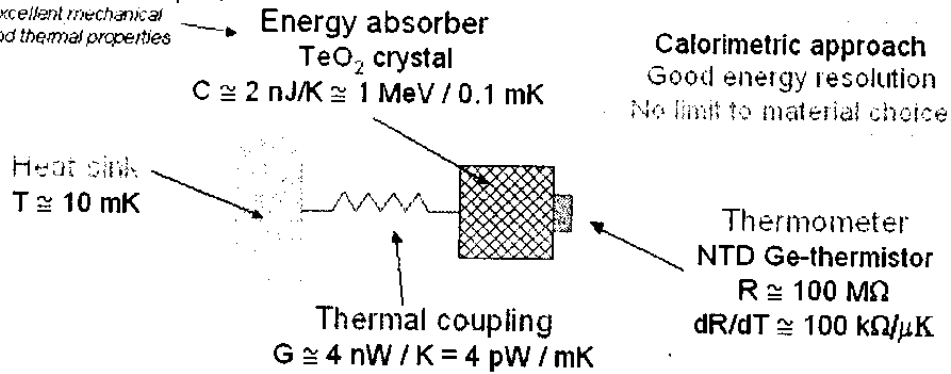
Effective PSD (SSE): ~ 45% of total statistics

**Heavy low activity shield:**

- 40 cm of lead
- PVC box flushed with nitrogen
- 2mm of cadmium
- 20 cm of polyethylene
- active veto (plastic scintillators)

## Low T Detector concepts

*Te dominates in mass the compound  
Excellent mechanical  
and thermal properties*



- Temperature signal:  $\Delta T = E/C \cong 0.1 \text{ mK}$  for  $E = 1 \text{ MeV}$
- Bias:  $I \cong 0.1 \text{ nA} \Rightarrow \text{Joule power} \cong 1 \text{ pW} \Rightarrow \text{Temperature rise} \cong 0.25 \text{ mK}$
- Voltage signal:  $\Delta V = I \cdot dR/dT \cdot \Delta T \Rightarrow \Delta V = 1 \text{ mV}$  for  $E = 1 \text{ MeV}$
- Signal recovery time:  $\tau = C/G \cong 0.5 \text{ s}$
- Noise over signal bandwidth (a few Hz):  $V_{\text{rms}} = 0.2 \text{ }\mu\text{V}$  In real life signal about a factor 2 - 3 smaller



Energy resolution (FWHM):  $\cong 1 \text{ keV}$

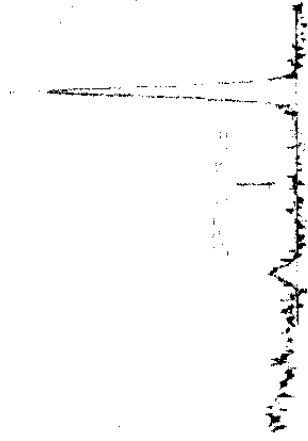
## Mi DBD II: results

Total statistic:  
 single 340 g detector +  
 4 x array +  
 20 x array (I and II) +  
 enriched crystal =  
 4.3 kg y

0.28

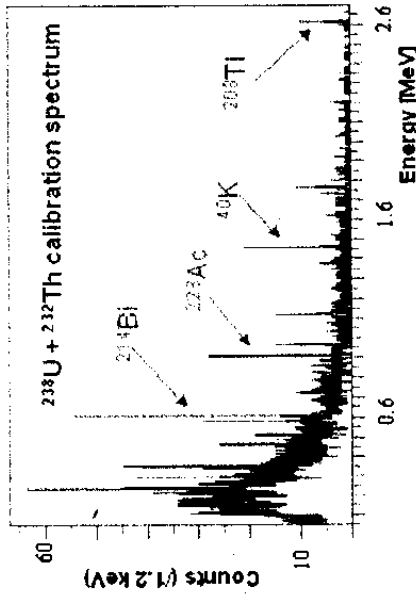
$\tau_{1/2} > 2.08 \cdot 10^{23}$  y @ 90% c.l.  
 (M.L. assuming flat  $^{238}\text{U}$  -  $^{232}\text{Th}$  and  $^{214}\text{Bi}$  peaks)

$\langle m \nu \rangle < 0.9 - 2.1$  eV



similar to 340 g crystal  
 thanks to improved detector design

- Performance of CUORICINO-type detectors ( $5 \times 5 \times 5$  cm<sup>3</sup> - 760 g):
- ◆ Detector base T: ~ 7 mK
  - ◆ Detector operation T: ~ 9 mK
  - ◆ Detector response: ~ 250 mV/MeV
  - ◆ FWHM resolution: ~ 3.9 keV @ 2.6 MeV



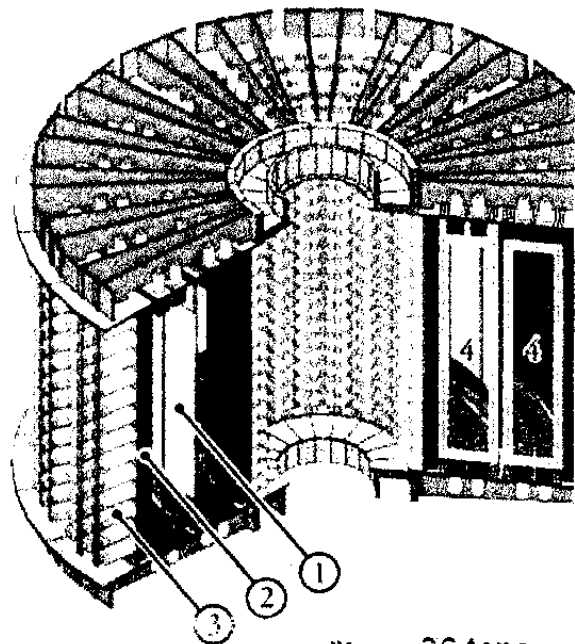
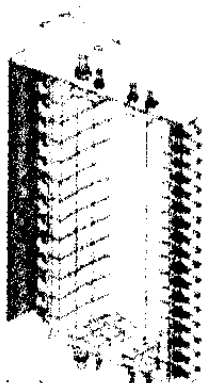
0205006

## Neutrinoless Experiment with Molybdenum III or Neutrino Ettore Majorana Observatory

Large Collaboration: 13 groups from Europe, USA and Japan

Passive source - Spectroscopic approach

$0\nu 2\beta$  sensitivity:  
 $T \sim 10^{24}$  y  
 $\langle m\nu \rangle \sim 0.1$  eV



Detector structure: 20 sectors

Source:

up to 10 kg of  $\beta\beta$  isotopes

(metal film or powder glued to mylar strips)

cylindrical surface:  $20 \text{ m}^2 \times 40\text{-}60 \text{ mg/cm}^2$

Tracking volume:

open octagonal drift cells (6180)

operated in Geiger mode

( $\sigma_1=0.5 \text{ mm}, \sigma_2=1 \text{ cm}$ )

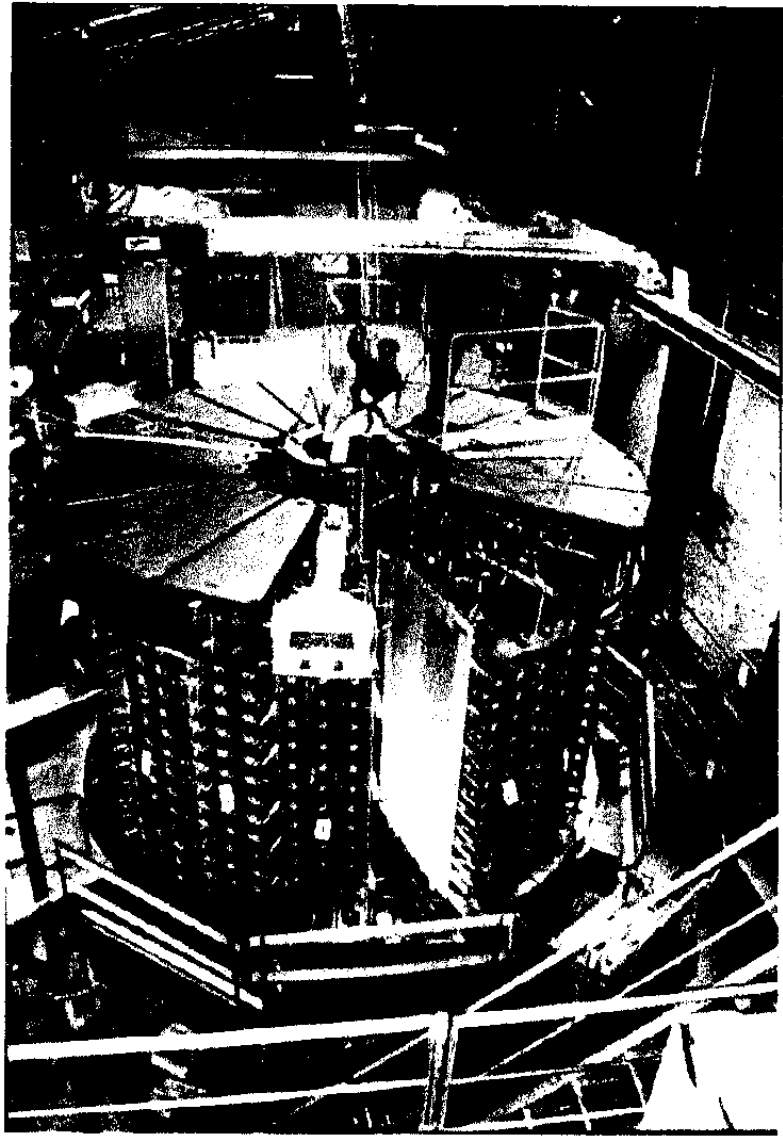
Calorimeter:

1940 plastic scintillators coupled to low activity PMs:

FWHM(1 MeV)  $\sim 11\text{-}14.5 \%$

magnetic Field (30 G) + Iron Shield (20 cm) + Neutron Shield (30 cm  $\text{H}_2\text{O}$ )

$m_{\text{tot}} \sim 36$  tons  
Low activity material



## Future projects

Experiment	Author	Isotope	Detector description	$T_{1/2}^{90}(y)$	$\langle m_{\nu} \rangle^*$
CUORE	Arnaboldi et al. 2001	$^{130}\text{Te}$	760 kg of $\text{TeO}_2$ bolometers	$7 \times 10^{26}$	0.027
EXO	Danavich et al 2000	$^{136}\text{Xe}$	11 enriched Xe TPC	$8 \times 10^{26}$	0.052
GEM	Zdesenko et al 2001	$^{76}\text{Ge}$	11 enriched Ge diodes in liquid nitrogen + water shield	$7 \times 10^{27}$	0.018
GENIUS	Klapdor-Kleingrothaus et al 2001	$^{76}\text{Ge}$	11 enriched Ge diodes in liquid nitrogen	$1 \times 10^{28}$	0.015
MAJORANA	Aalseth et al 2002	$^{76}\text{Ge}$	0.5 t enriched Ge segmented diodes	$4 \times 10^{27}$	0.025
DCBA	Ishihara et al 2000	$^{150}\text{Nd}$	20 kg enriched Nd layers with tracking	$2 \times 10^{25}$	0.035
CAMEO	Reifm et al 2001	$^{116}\text{Cd}$	11 $\text{CdWO}_4$ crystals in liquid scintillator	$> 10^{26}$	0.069
CANDLES	Kishimoto et al	$^{48}\text{Ca}$	several tons of $\text{CaF}_2$ crystal in liquid scintillator	$1 \times 10^{26}$	
GSO	Danavich 2001	$^{160}\text{Gd}$	21 $\text{Gd}_2\text{SiO}_5:\text{Ce}$ crystal scintillator in liquid scintillator	$2 \times 10^{26}$	0.065
MOON	Ejiri et al 2000	$^{100}\text{Mo}$	34 t natural Mo sheets between plastic scintillator	$1 \times 10^{27}$	0.036
Xe	Laccharinga et al 2001	$^{136}\text{Xe}$	1.56 t of enriched Xe in liquid scintillator	$5 \times 10^{26}$	0.066
XMASS	Moriyama et al 2001	$^{136}\text{Xe}$	10 t of liquid Xe	$3 \times 10^{26}$	0.086

\* Staudt, Mito, Klapdor-Kleingrothaus *Europh. Lett* 13 (1990) 31

Bigger is better,

IFF the TOTAL background rate is kept  $\sim$  constant! This is the major challenge.

POSITIVE SIGNAL IF INVERTED HIERARCHY

# GENIUS

Klapdor-Kleingrothaus HV hep-ph/0103074

## Very large mass extension of the active source Ge-diodes approach

### GOAL:

- $m_\nu$  sensitivity  $\sim 10$ - $20$  meV
- test all possible  $m_\nu$  scenarios allowed by oscillation experiments

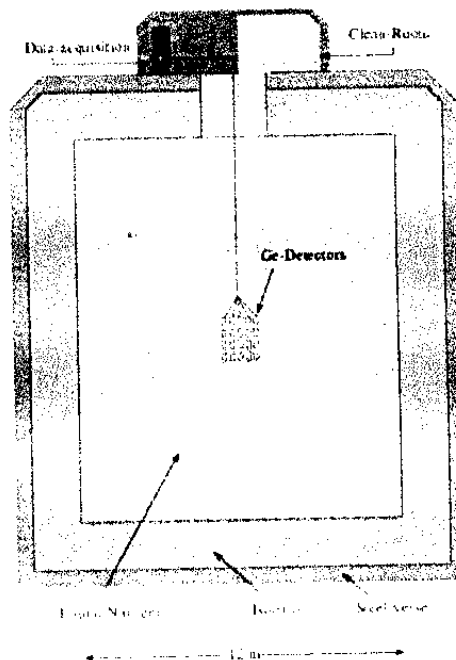
- Reduce Background
- Enlarge mass

### SOLUTION:

large number (400) of naked i.e. (86%) diodes (total mass  $\sim 1$  ton)  $\longrightarrow$  10 tons suspended in a very large container of liquid nitrogen (clean shield)

Gran Sasso or USA underground laboratory

DMT Solar Neutrinos







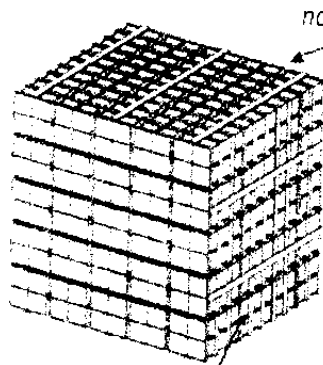
# The CUORE set-up

## Cryogenic Underground Observatory for Rare Events

LBL - U. Como - U. Firenze - Legnaro (LNL)  
LNGS - U. Milano - USC - U. Zaragoza

CUORE = closely packed array of 1000 detectors  
25 towers - 10 modules/tower - 4 detector/module

↳ Cubic structure, ideal for active shielding

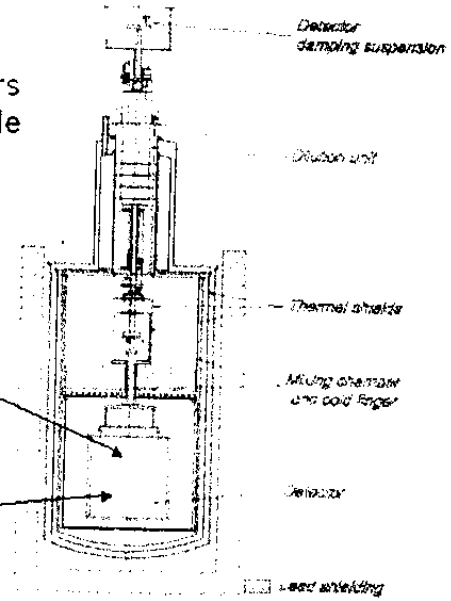


no more inert Cu plates facing crystals

M = 760 kg

Each tower is a CUORICINO-like detector

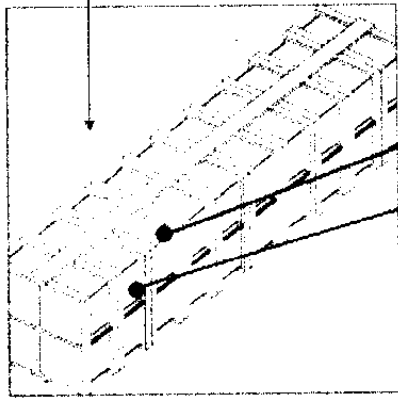
Special dilution refrigerator



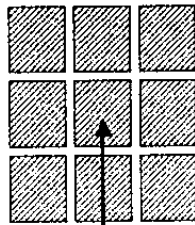
## The CUORICINO set-up

CUORICINO = tower of 13 modules, 4 detector (760 g) each  
M = 40 kg

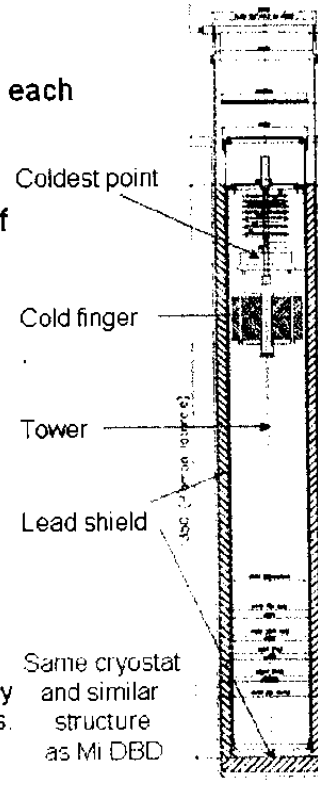
New configuration: 2 planes will consist of  
340 g detectors arranged in a 3 · 3 matrix



Plane section



This detector will be completely  
surrounded by active materials.  
Substantial improvement  
in BKG reduction



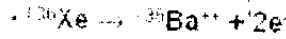


# EXO

Danilov M. et al. Phys. Lett. B-480 (2000) 12

## Large Xenon TPC with single Ba<sup>+</sup>-ion detection via laser tagging

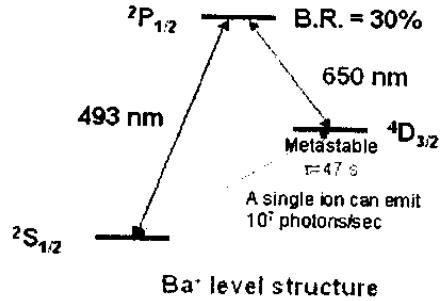
- Caltech
- IBM Almaden
- INFN Padova
- ITEP Mosca
- UC Irvine
- Stanford University
- U. of Alabama
- U. of Neuchatel
- U. of Torino
- U. of Trieste
- WIPP Carlsbad



- Double Laser Pulse
- Optical Spectroscopy

Strong background reduction

M. Moe PRC 44(1991)321



### Xenon Properties:

- active source approach
- continuous purification
- no activation
- versatility
- depleted Xe: bkg check
- easy isotopical enrichment

### Requirements for high $0\nu 2\beta$ sensitivity:

- Large mass (1-10 t)
- High Density Isotopically Enriched (90%) Xe TPC
- Good Energy Resolution (2%)
- Low Background Environment
- Ba<sup>++</sup> Neutralization
- Long Ba lifetime in detector chamber

$$T^{0\nu} > 8.3 \times 10^{26} \text{ y (90\% C.L.)} - \langle m_{\nu} \rangle < (0.05-0.14) \text{ eV ln } 5 \text{ y}$$



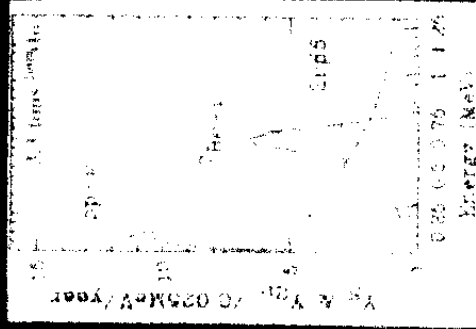
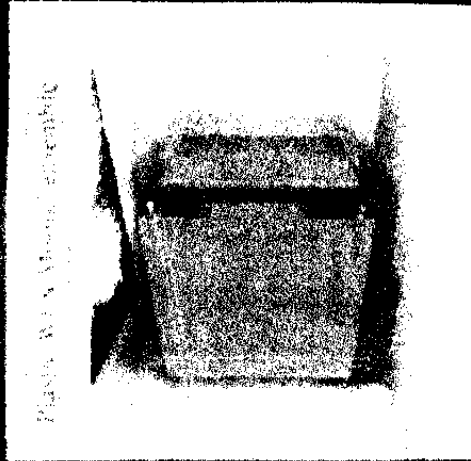
# MOON Detector Supermodule of Mo-Scintillator

Realistic purity of  $10^{-12}$  Bq/ton (0.1 ppt) U-Th. Position read down

Options: 1. Plastic fibers Moduls Ensemble


2. 5m x 2.5m x 1m with 0.8 ton Mo (Nub-Arcadia 1991)

3. Liquid scintillator with WLS Read out



# XLASS – liquid xenon scintillation detector

Location: Kamioka



2.5 m

- Detection reaction: ES ( $\nu + e \rightarrow \nu + e$ )
- 23 t (10 t fid.) detector
- 30cm self-shield ( $\rho = 3.06 \text{ g/cm}^3$ )
- 1350 3" PMTs
- 42,000 scintillation photons/MeV
- No inactive buffer (23t volume active)

**Background requirements:** ( $\leq 1 \text{ E}^{-7} \text{ day}^{-1}$ )

$^{136}\text{Xe } 2\nu\text{-}\beta\beta$ :  $t_{1/2}^{\text{theory}} = 8 \times 10^{21} \text{ y}$   
 $\Rightarrow 1000 \text{ events/d}$   
 $\Rightarrow$  isotope separation factor 10-100!

**Trace contaminations:**

$^{85}\text{Kr}$  ( $t_{1/2} = 10.7 \text{ y}$ ):  $< 4 \times 10^{-15} \text{ gKr/gXe}$   
 $^{42}\text{Ar}$  ( $t_{1/2} = 33 \text{ y}$ ):  $< 4 \times 10^{-11} \text{ gAr/gXe}$   
 U/Th:  $< 4 \times 10^{-16}$

**Muon induced:**  
 In-situ spallation: 2/day ??  
 (assuming 10 mb)

**External Background:**  
 Similar to BOREXINO design  
 Self-shielding  $\Rightarrow$  fiducial volume

Y. Suzuki et al.)