Current issues in neutrino physics

André Rubbia
ETH Zürich

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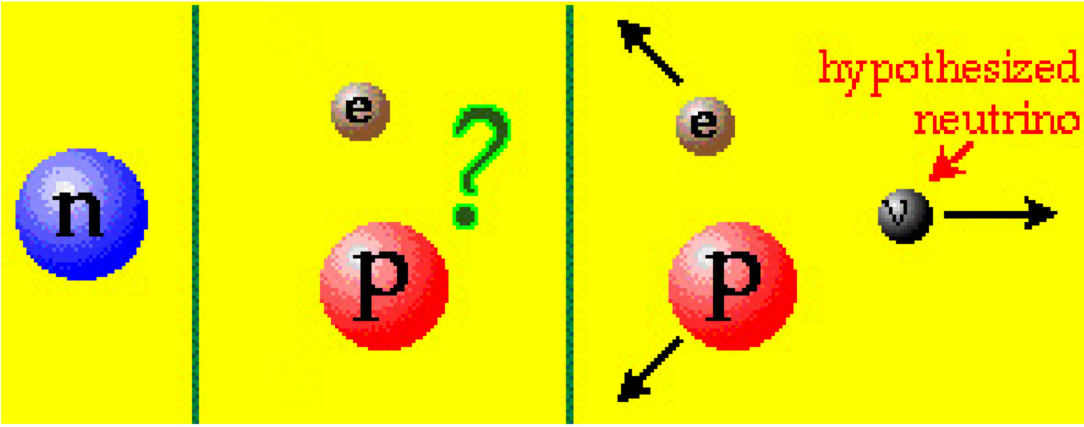
History

$$n \rightarrow p + e^{-} + \nu$$

Neutrino postulate:

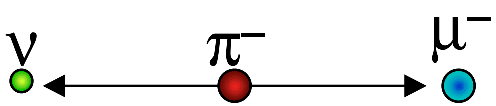


W. Pauli (1900-1958)

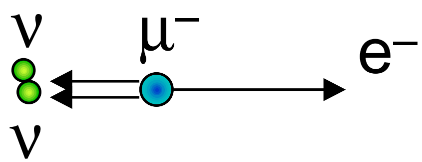
First detected in 1956 by Reines & Cowan

Neutrinos are only sensitive to the weak (and gravitational) forces

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu$$



$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \nu$$



The neutrino intrinsic properties

Neutrino is hard to detect

still mostly a mystery!

Electric charge	0
Angular momentum (spin)	1/2
Helicity	Appears 100% left-handed
Interactions	Only weak
Rest mass	?
Lifetime	?
Anomalous magnetic moment	?
Intrinsic nature Dirac-Majorana	?

*I will concentrate on the quest for **neutrino oscillations*** $\Rightarrow$

Weak charged currents

By symmetry arguments, one would expect quark and lepton weak currents to have similar structure:

Quarks charged current:

$$(\bar{u} \quad \bar{c} \quad \bar{t})_L \gamma^\mu U_q \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

$$\begin{pmatrix} d© \\ s© \\ b© \end{pmatrix} \equiv U_q \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak eigenstates **Flavor eigenstates**

Leptons charged current:

$$(\bar{e} \quad \bar{\mu} \quad \bar{\tau})_L \gamma^\mu U_l \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \equiv U_l \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak eigenstates **Mass eigenstates**

However, in the Standard Model, neutrinos are massless (degenerate)

$\Rightarrow U_l \equiv 1$

$\Rightarrow$ $$(\bar{e} \quad \bar{\mu} \quad \bar{\tau})_L \gamma^\mu \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L$$

Neutrino flavor oscillations (in vacuum)

In vacuum: ***Time evolution of a neutrino mass eigenstate ν_i (=stationary state of the free Hamiltonian)***

B. Pontecorvo (1957)

$$e^{-iE_i t}$$

$E_i \equiv$ energy of state

$$E_i = \sqrt{\vec{p}^2 + m_i^2}$$

Neutrino state produced in weak decay:

$$|\nu(t=0)\rangle \equiv |\nu_\alpha\rangle$$

($\alpha \equiv e,\mu,\tau$)

$$|\nu(t=0)\rangle \equiv |\nu_\alpha\rangle = \sum_j U_{\alpha j} |\nu_j\rangle \Rightarrow |\nu(t)\rangle = \sum_j U_{\alpha j} \underbrace{e^{-iE_j t}}_{\text{phase}} |\nu_j\rangle$$

phase

Neutrino flavor oscillation probability:

$$P_\alpha \equiv |\langle \nu_\alpha | \nu(t)\rangle|^2$$

Oscillation probability

- The case with two neutrinos:
  - →A mixing angle: θ
  - →A mass difference:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\Delta m^2 = m_2^2 - m_1^2 \quad (eV^2)$$

- The oscillation probability is:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 \frac{L}{E}\right)$$

where L = distance between source and detector (km)
E = neutrino energy (GeV)

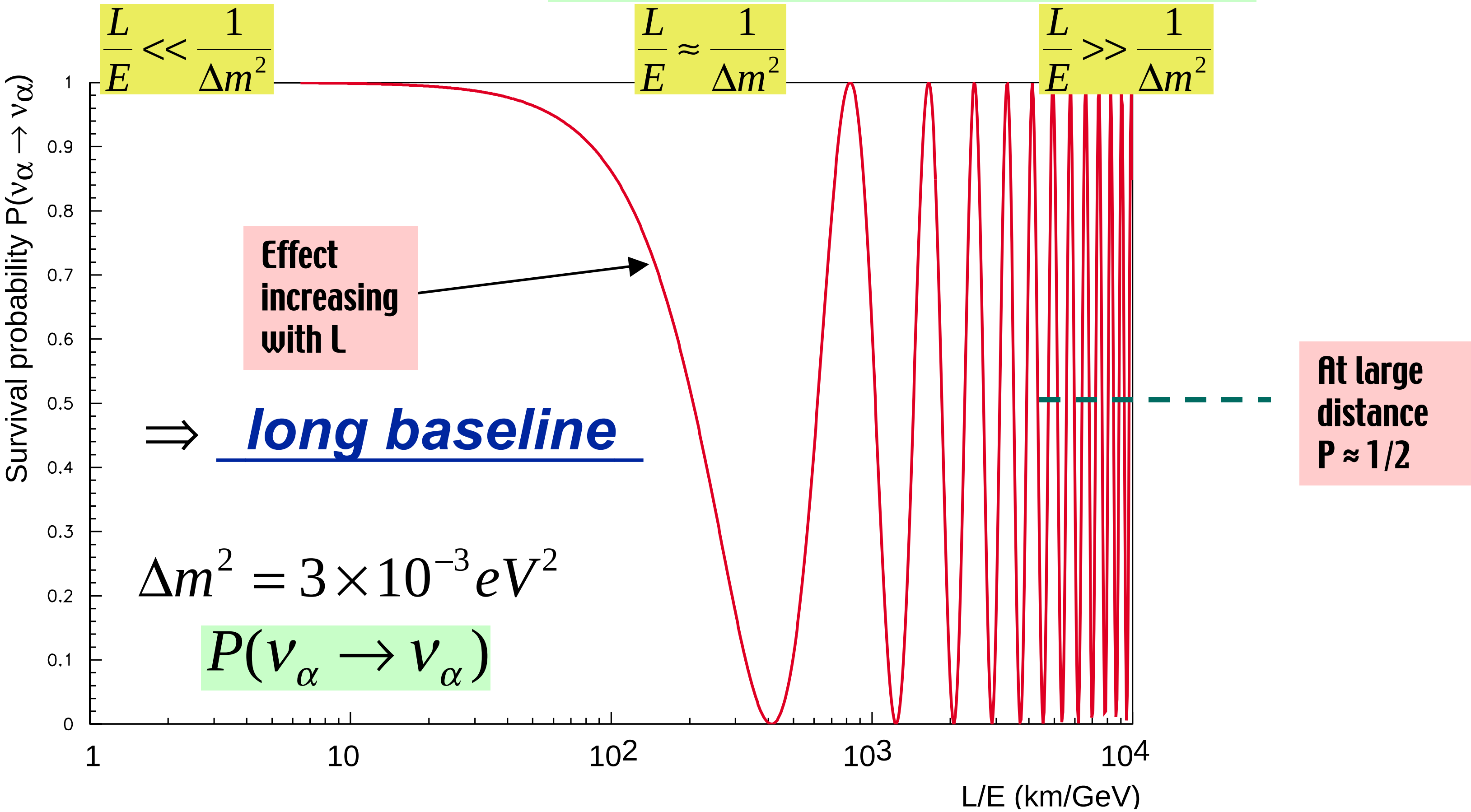
Neutrino oscillation phenomenology

- In interesting cases, the oscillations decouple so that they are approximated by a ***two-neutrino oscillation*** :

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27 \ \Delta m_{12}^2 L}{E}\right)$$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27 \ \Delta m_{12}^2 L}{E}\right)$$



Oscillation map - "allowed regions"

Two-neutrino oscillation

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

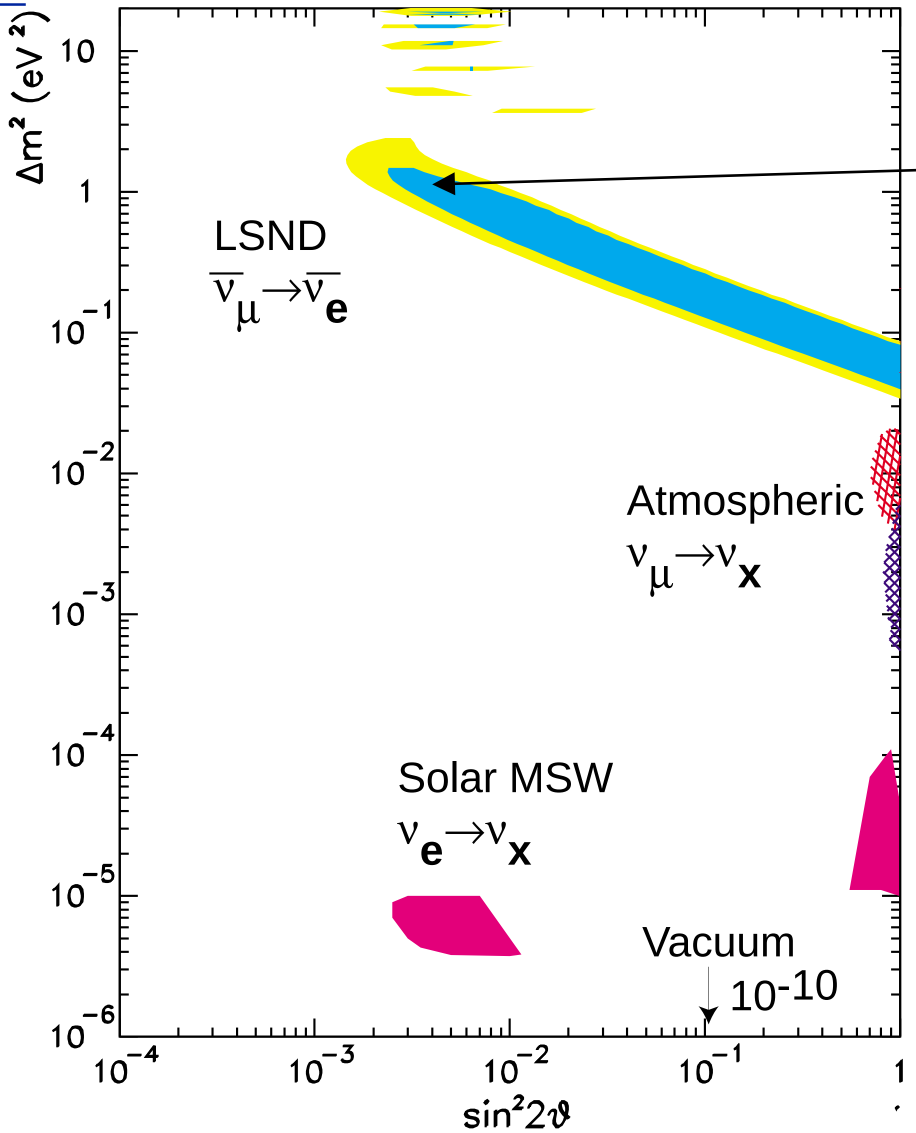
Electron excess

$\nu_\mu \rightarrow \nu_x$

Muon deficit

$\nu_e \rightarrow \nu_x$

Electron deficit



$\Delta m^2_{LSND} \approx 1\ eV^2$
$\sin^2 2\theta \approx 0.003$

$\Delta m^2_{atm} \approx 10^{-3}\text{–}10^{-2}\ eV^2$
$\sin^2 2\theta \approx 1$

$\Delta m^2_{solar} \approx 10^{-5}\ eV^2$
$\sin^2 2\theta \approx 0.8$ or 0.008

Matter enhanced (MSW effect)

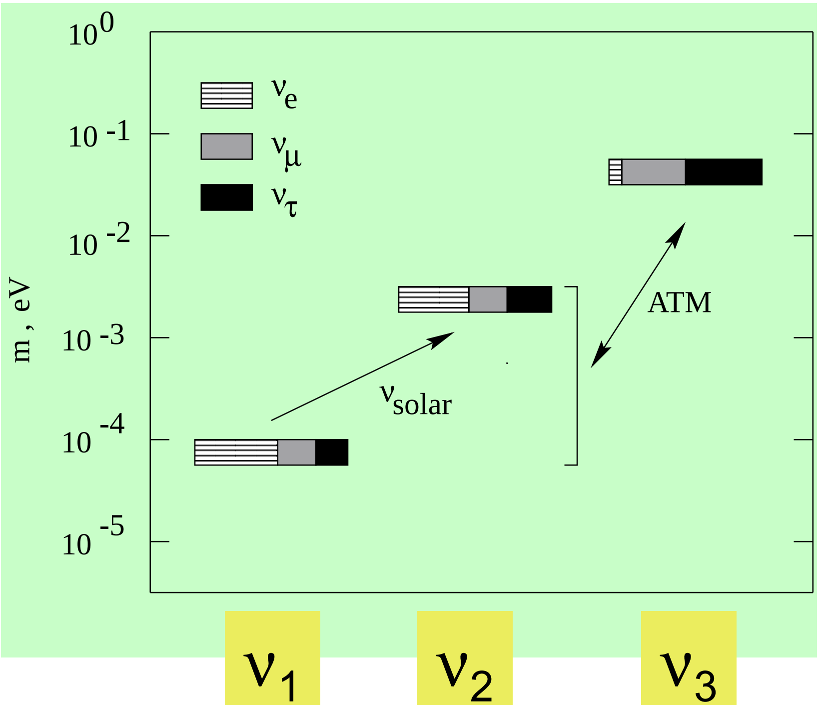
$\Delta m^2_{solar} \approx 10^{-10}\ eV^2$
$\sin^2 2\theta \approx 0.8$

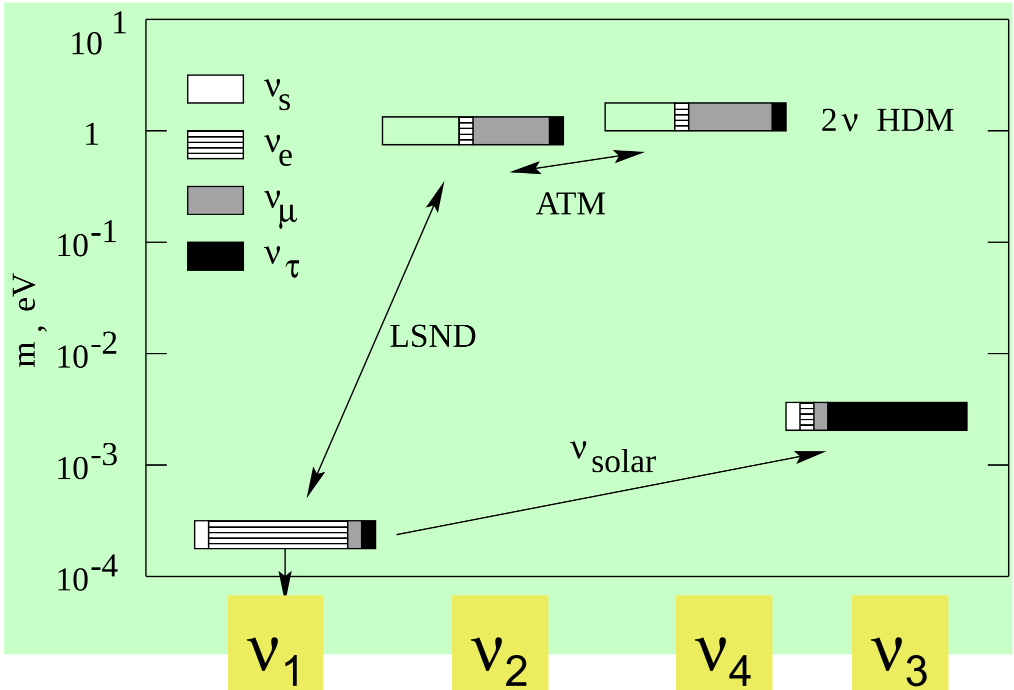
Vacuum oscillation

Where do we stand with the models?

- The three-flavor mixing ***cannot accommodate all experiments***
  - → Only two independent Δm^2 with three neutrinos
  - → 3 distinct Δm^2 regions $\Delta m^2_{solar} << \Delta m^2_{atm} << \Delta m^2_{LSND}$ required to accommodate solar, atmospheric and LSND data requires
  - → transitions involving ***"sterile" states*** could be occurring as well

Smirnov, hep-ph/9907296



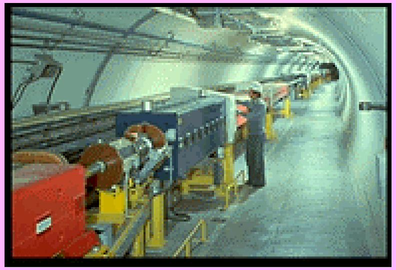


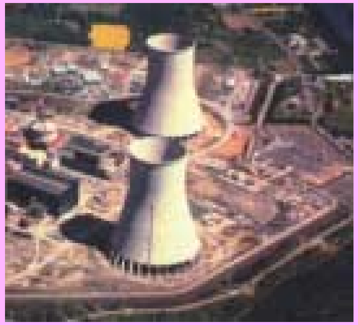
The “challenging” sources of neutrinos

Apart from the artificial sources, Nature has provided us with natural sources of neutrinos

Artificial sources

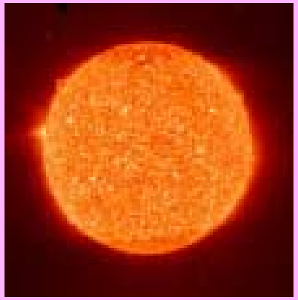
Accelerators





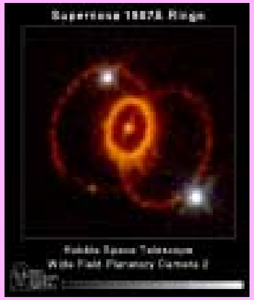
Reactors

Natural sources



Solar

Atmospheric



Supernovae

BigBang, SN relic, UHE

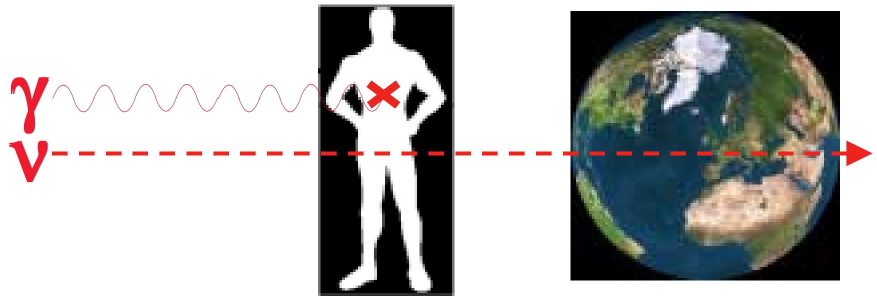
These have all been detected!

Except these!

Neutrino and rare process physics

- The performance of a **neutrino detector** is ***proportional*** to its ***total mass*** and also to its ***geometrical granularity*** with which the events can be reconstructed.

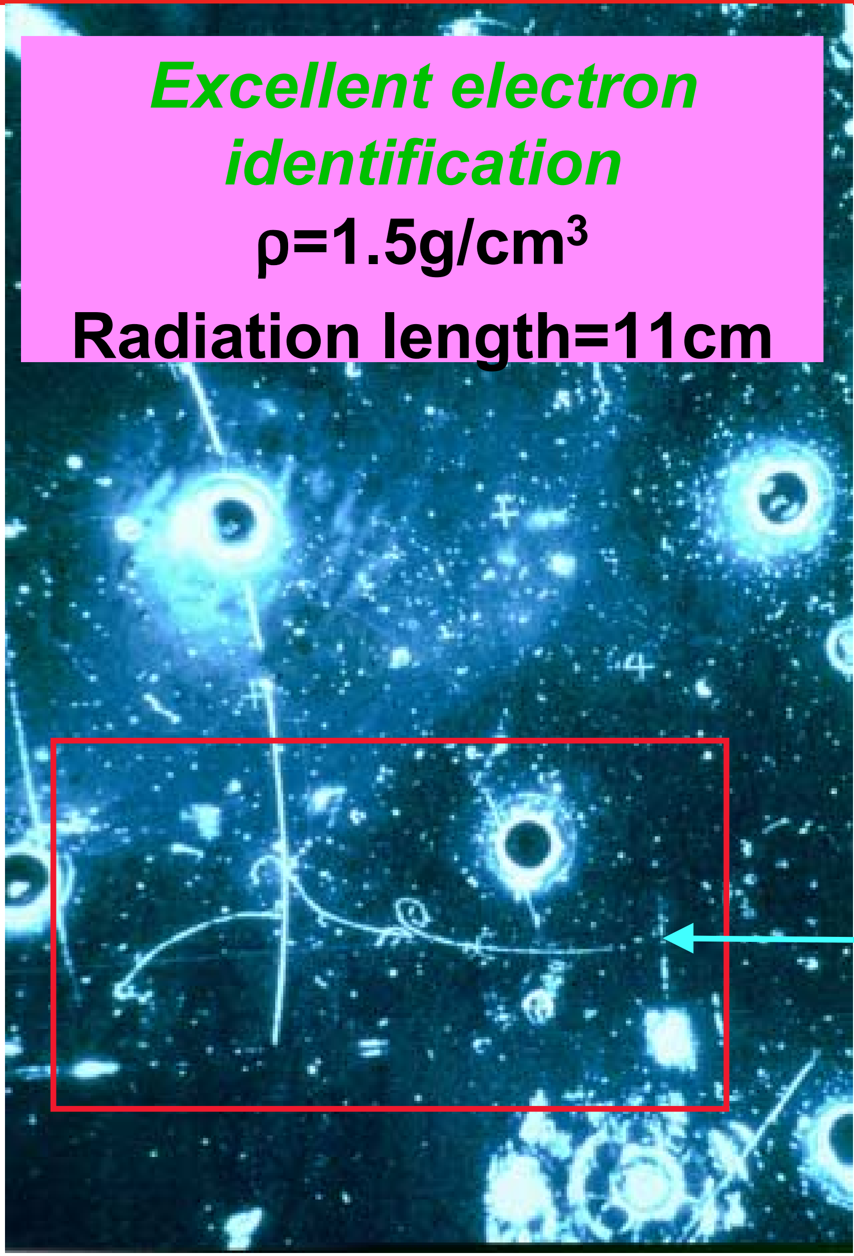
What we get for 5 ktons of target:



- **Atmospheric neutrinos:**
  - ≈**1000** atm CC events / year
  - **≈5** ν_τ CC /year from oscillations
- **Solar neutrinos:**
  - **17500×f_{8B}** solar neutrinos / year @ E > 5 MeV
- **Neutrinos from CERN (CNGS):**
  - **13600** ν_μ CC per 4.5×10^{19} pots @ L = 730 km
- **Neutrino factory:**
  - **1200** ν_μ CC per 10^{20} μ @ L = 7400 km
- **Number of targets for nucleon stability:**
  - 3×10^{33} nucleons ⇒ $\boldsymbol{\tau_p}$ **(10^{32} years) > 6 × T(yr) × ε** @ 90 C.L.

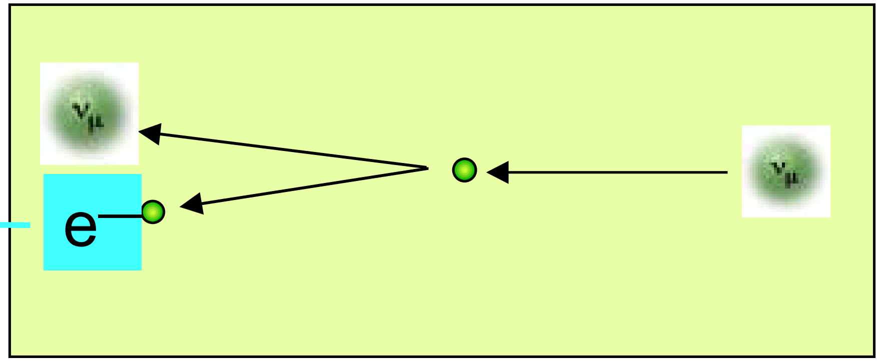
A bonus!

Discovery of neutral currents (1973)



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

E_e=385±100MeV
θ_e=*1.4±1.4°*



Gargamelle, Phys. Lett. B46 (1973) 121

Oscillation map - “allowed regions”

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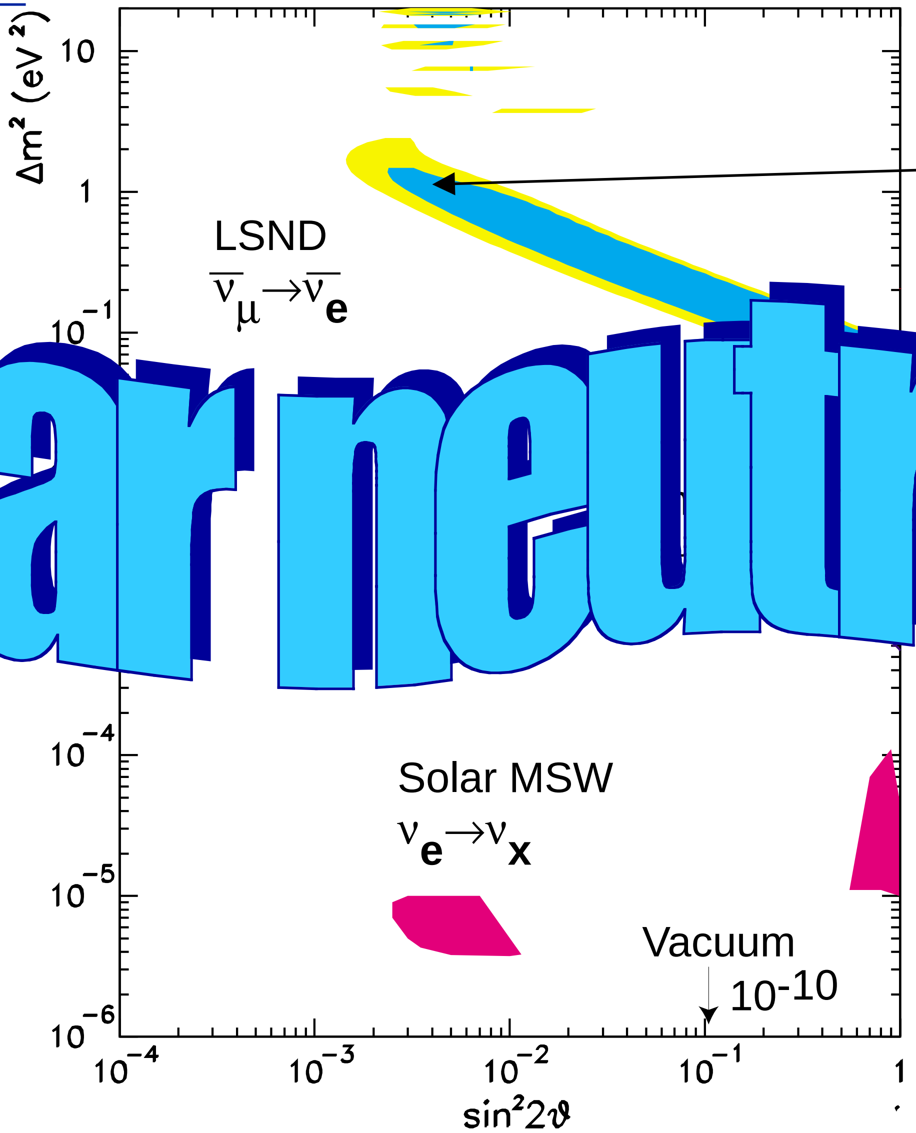
Electron excess

$\nu_e \rightarrow \nu_x$

Electron deficit



Solar neutrinos

$\Delta m^2_{LSND} \approx 1\ eV^2$

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Matter enhanced (MSW effect)

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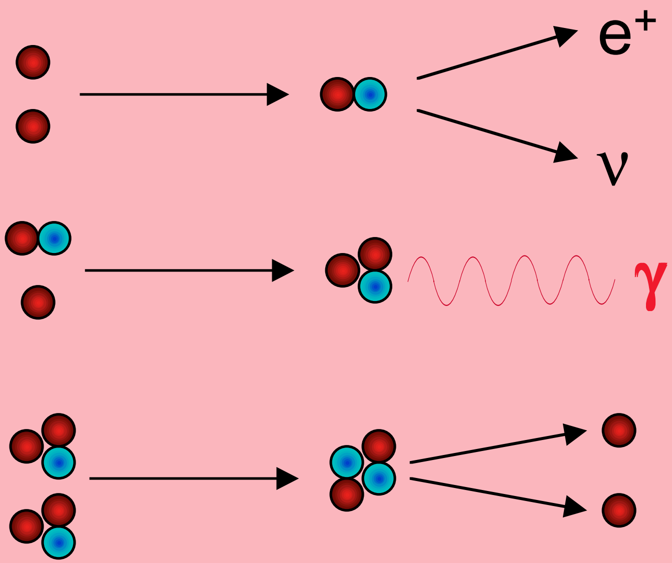
Vacuum oscillation

Solar neutrinos

Stellar energy comes from **NUCLEAR FUSION** in core

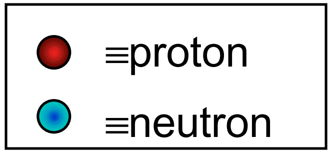
pp cycle:

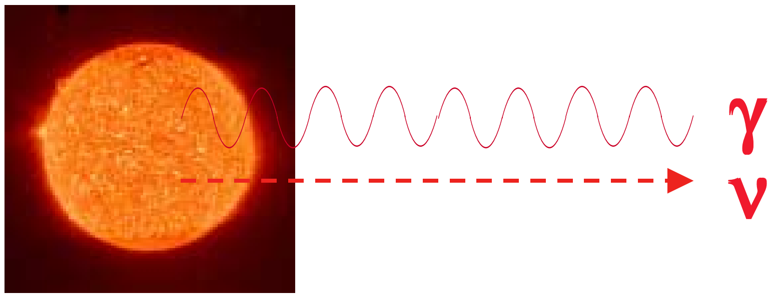


$$p + p \rightarrow D + e^+ + \nu$$

$$p + D \rightarrow {}^3He + \gamma$$

$${}^3He + {}^3He \rightarrow {}^4He + 2p$$





$4H \rightarrow {}^4He + \gamma + \nu$

light,heat — neutrinos

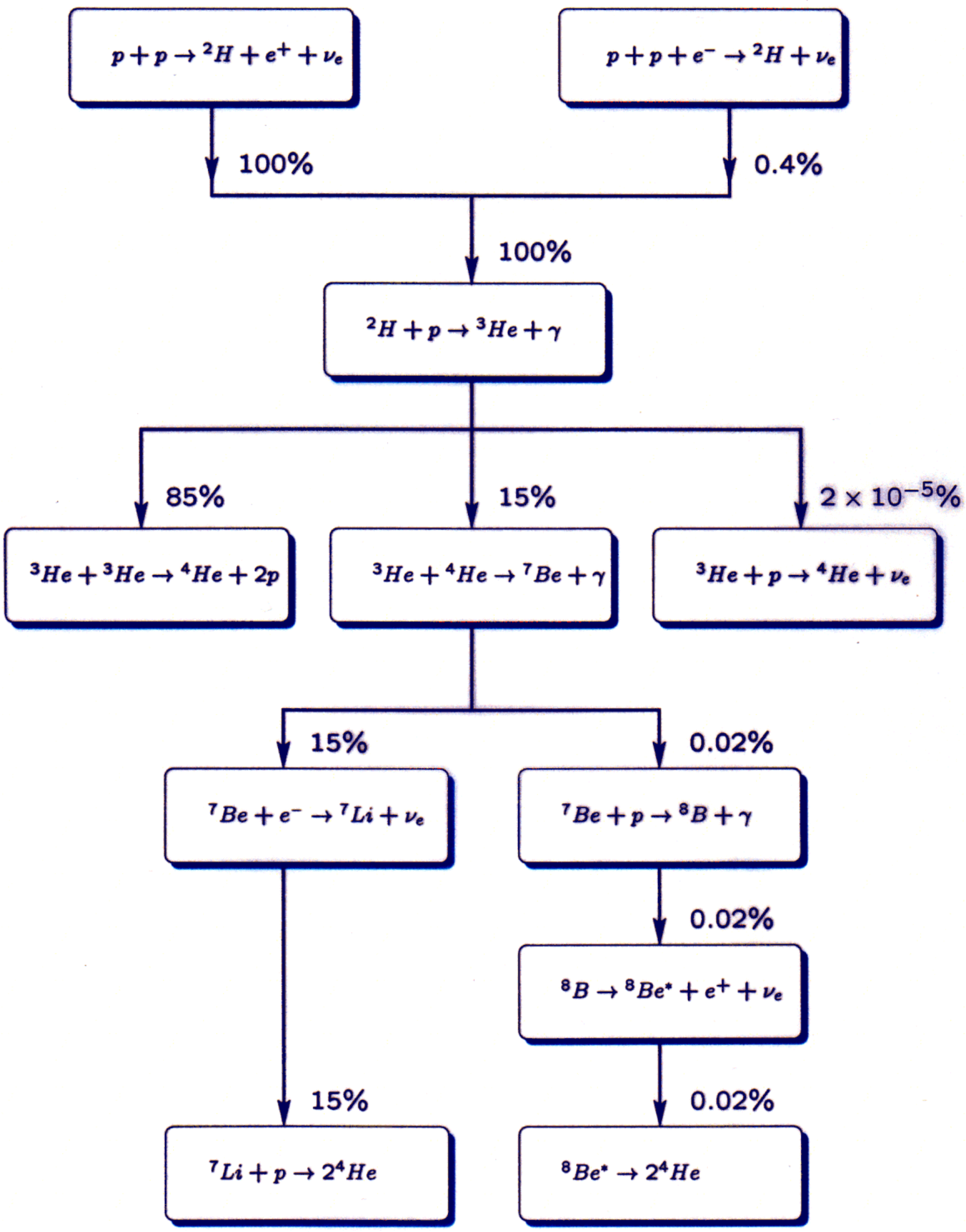
Q=26.73 MeV; $\langle E\nu_e \rangle$ = 0.265 MeV

Stars are strong neutrino sources!

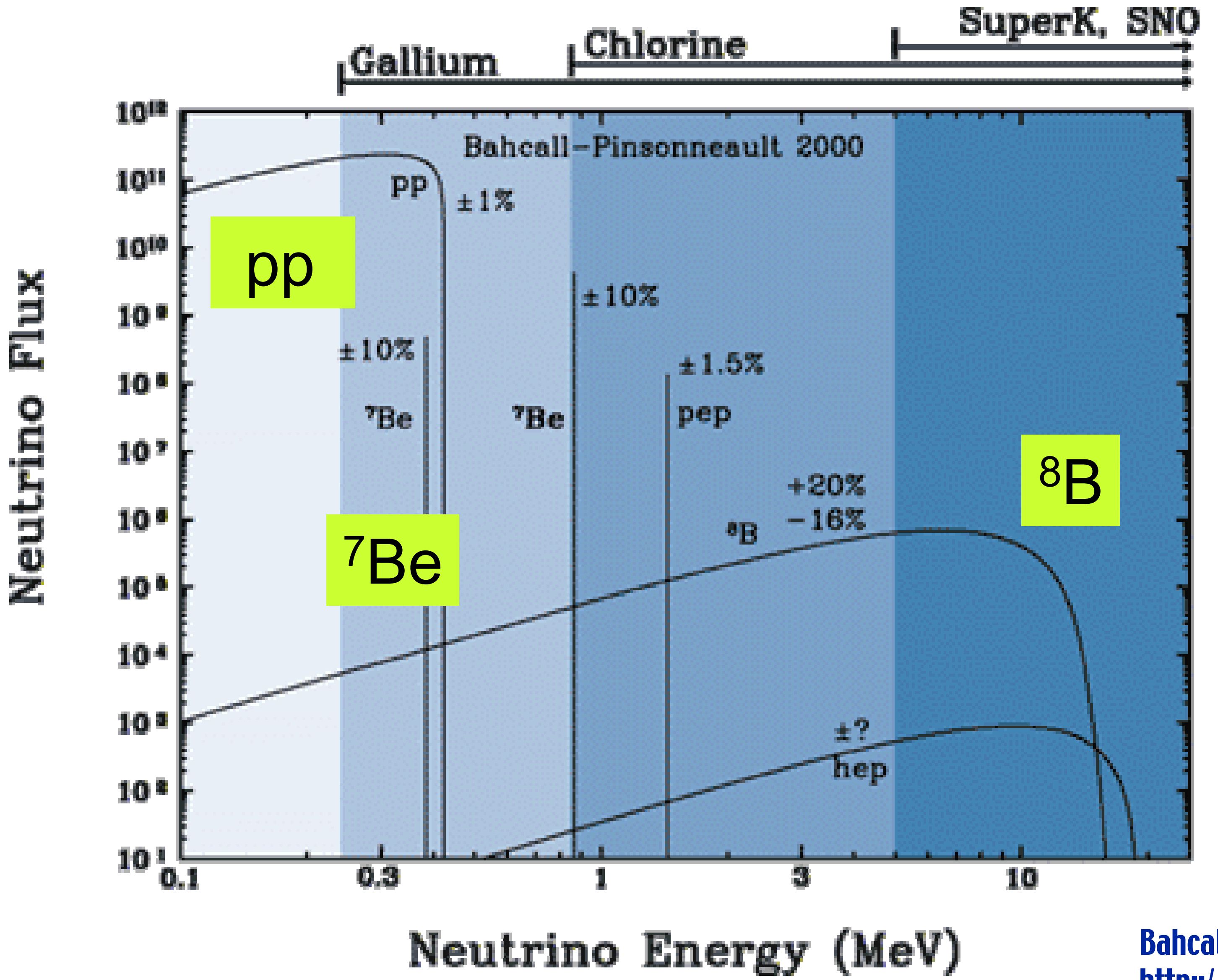
$$\phi_{Earth} \approx 10^{11} \quad \nu / cm^2 / s$$

Day & night!

PP chain


$p+p \rightarrow {}^2H + e^+ + \nu_e$
$p+p+e^- \rightarrow {}^2H + \nu_e$
100%
0.4%
100%
${}^2H + p \rightarrow {}^3He + \gamma$
85%
15%
$2 \times 10^{-5}\%$
${}^3He + {}^3He \rightarrow {}^4He + 2p$
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
${}^3He + p \rightarrow {}^4He + \nu_e$
15%
0.02%
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
${}^7Be + p \rightarrow {}^8B + \gamma$
0.02%
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
15%
0.02%
${}^7Li + p \rightarrow 2{}^4He$
${}^8Be^* \rightarrow 2{}^4He$

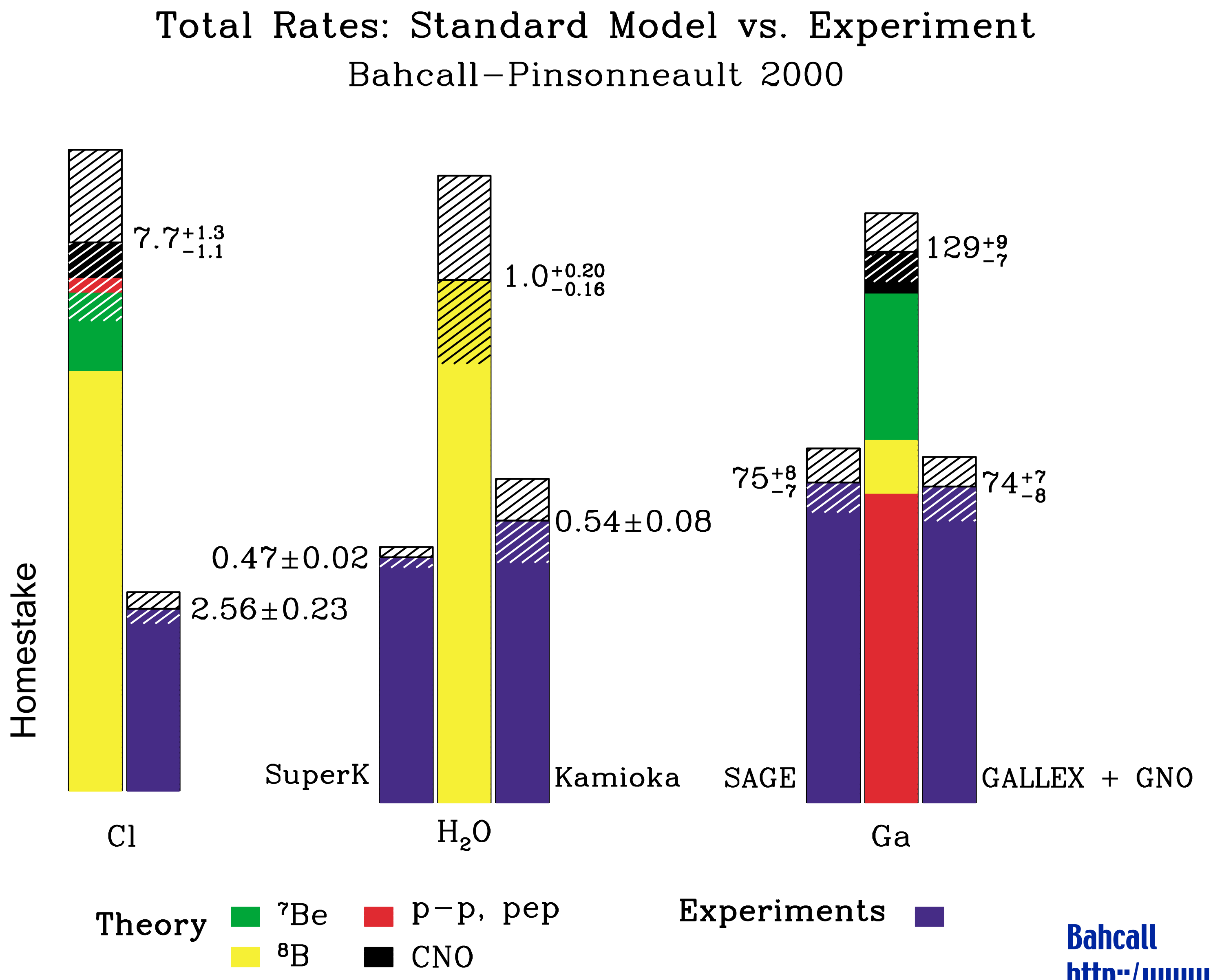
Predicted solar neutrino spectrum



Experimental threshold

Bahcall
http::/www.sns.ias.edu/~jnb

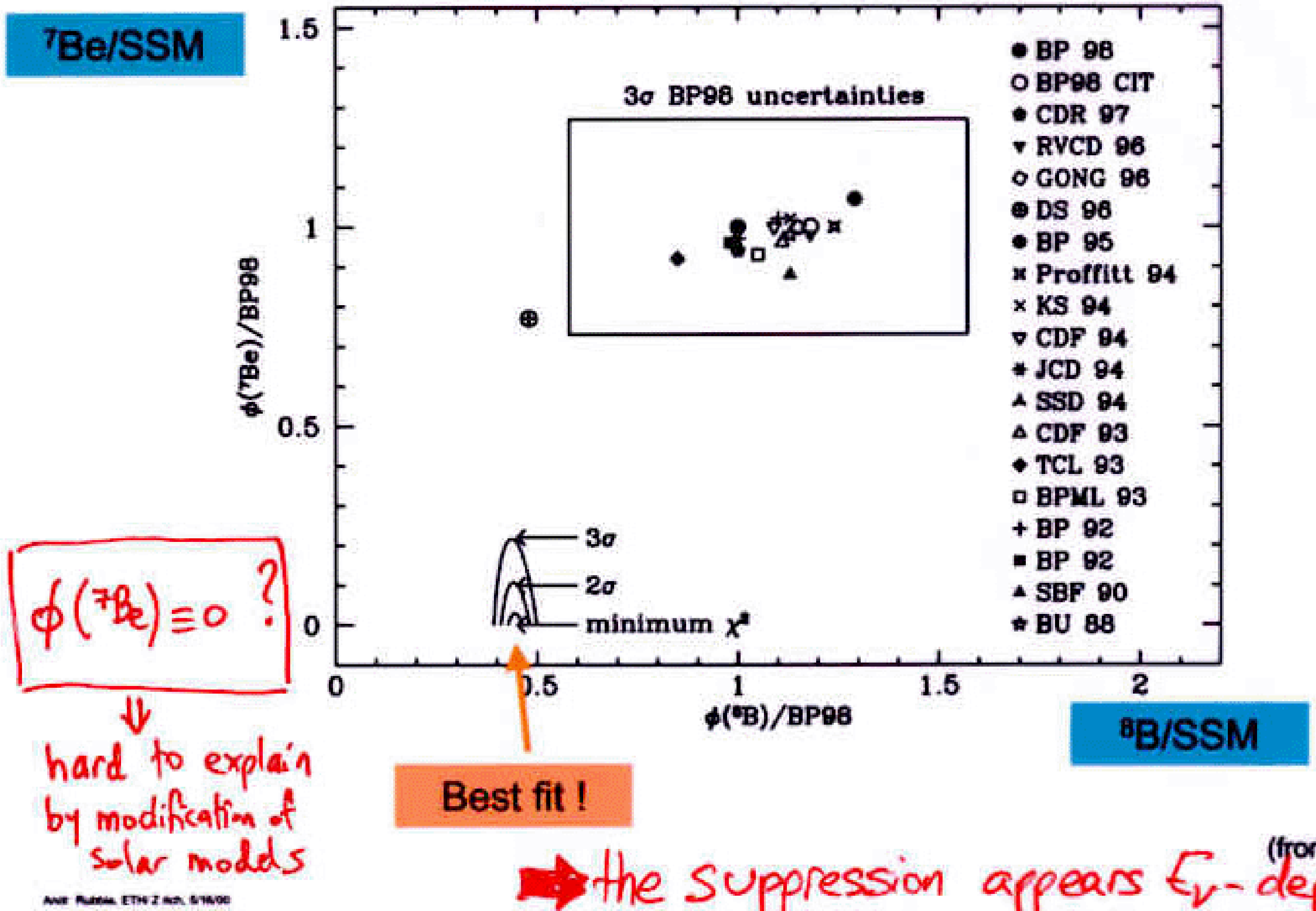
The solar neutrino problems



Bahcall
http::/www.sns.ias.edu/~jnb

Fitted Be & B rates versus predictions

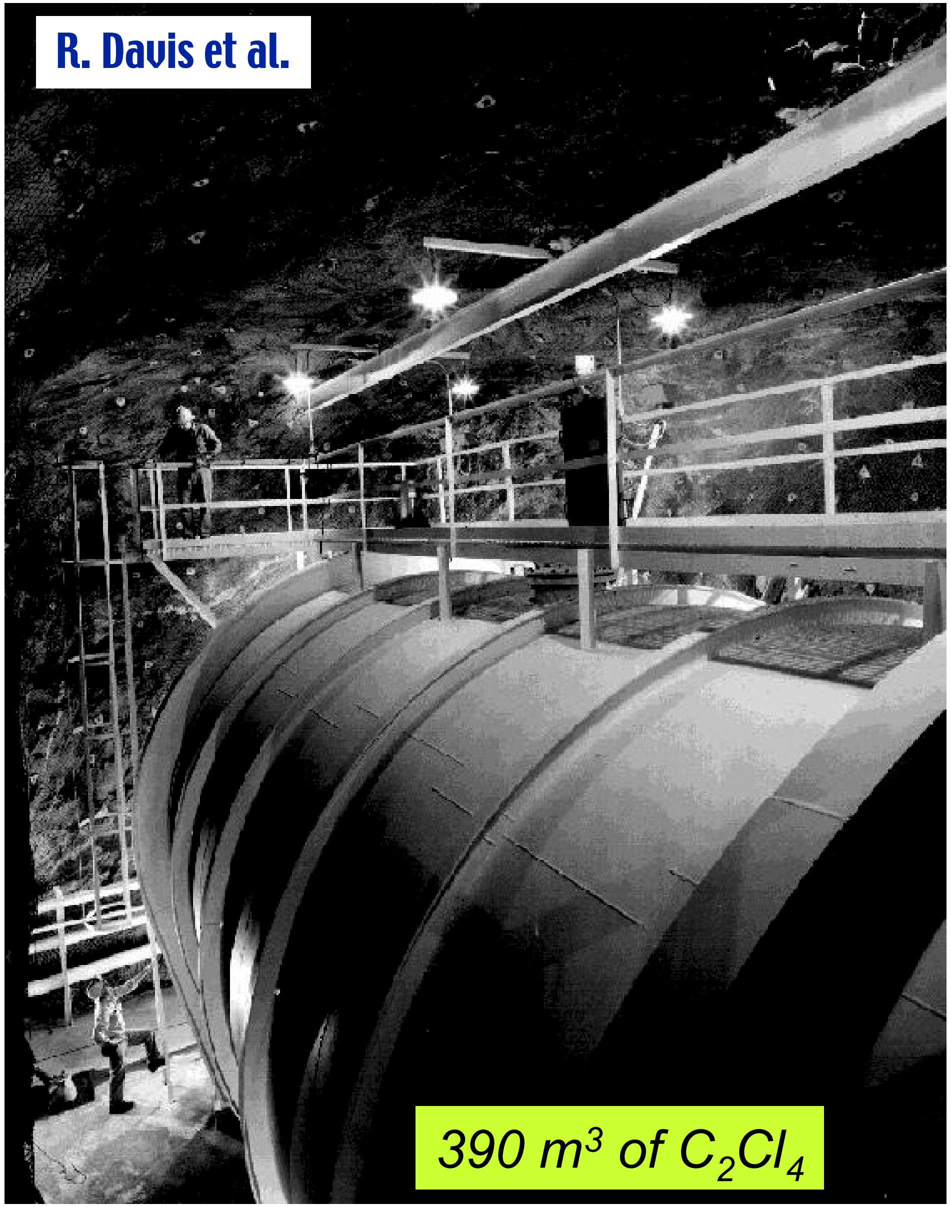
combining experiments + luminosity constraint



(from Bahcall)

➡ the suppression appears E_ν-dependent

Chlorine experiment– Homestake Mine



$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

$E_\nu > 814$ KeV

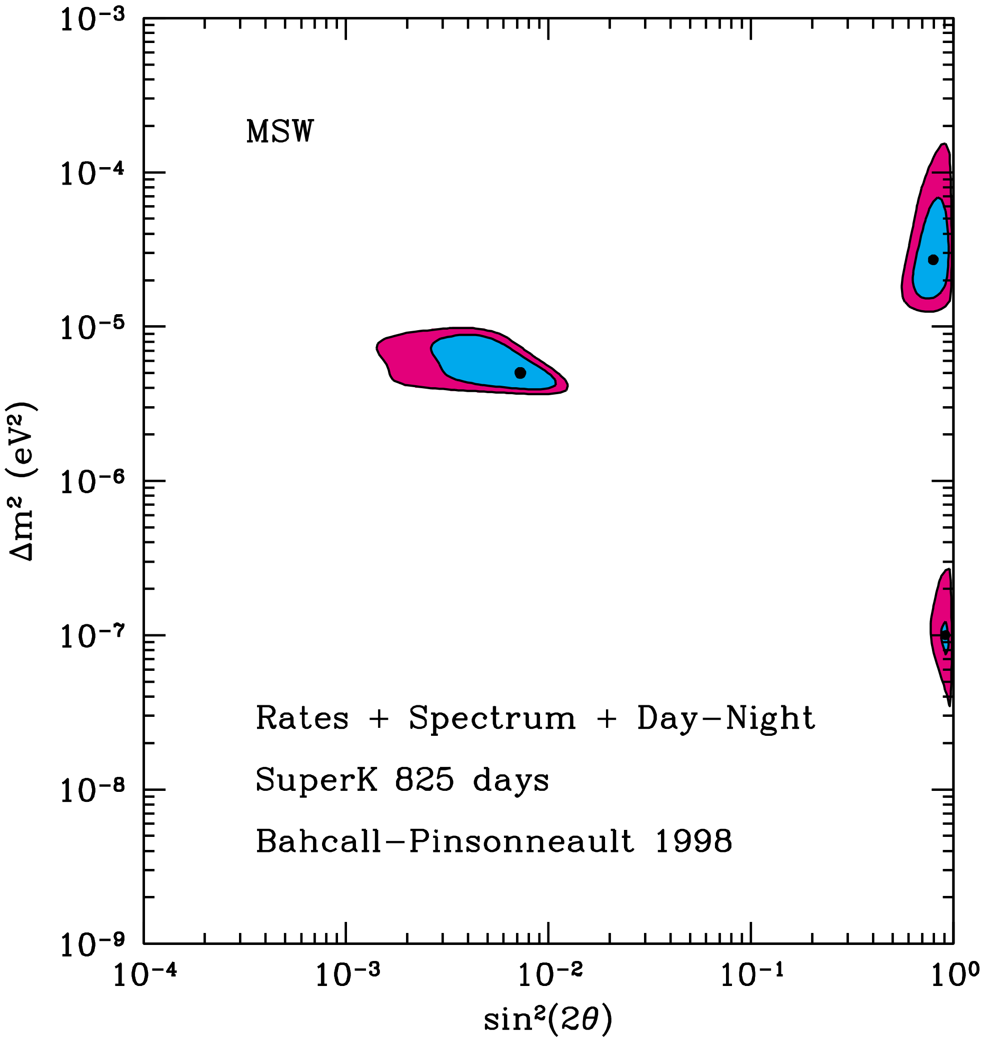
Expected rate: ***9.5–1.4 SNU***

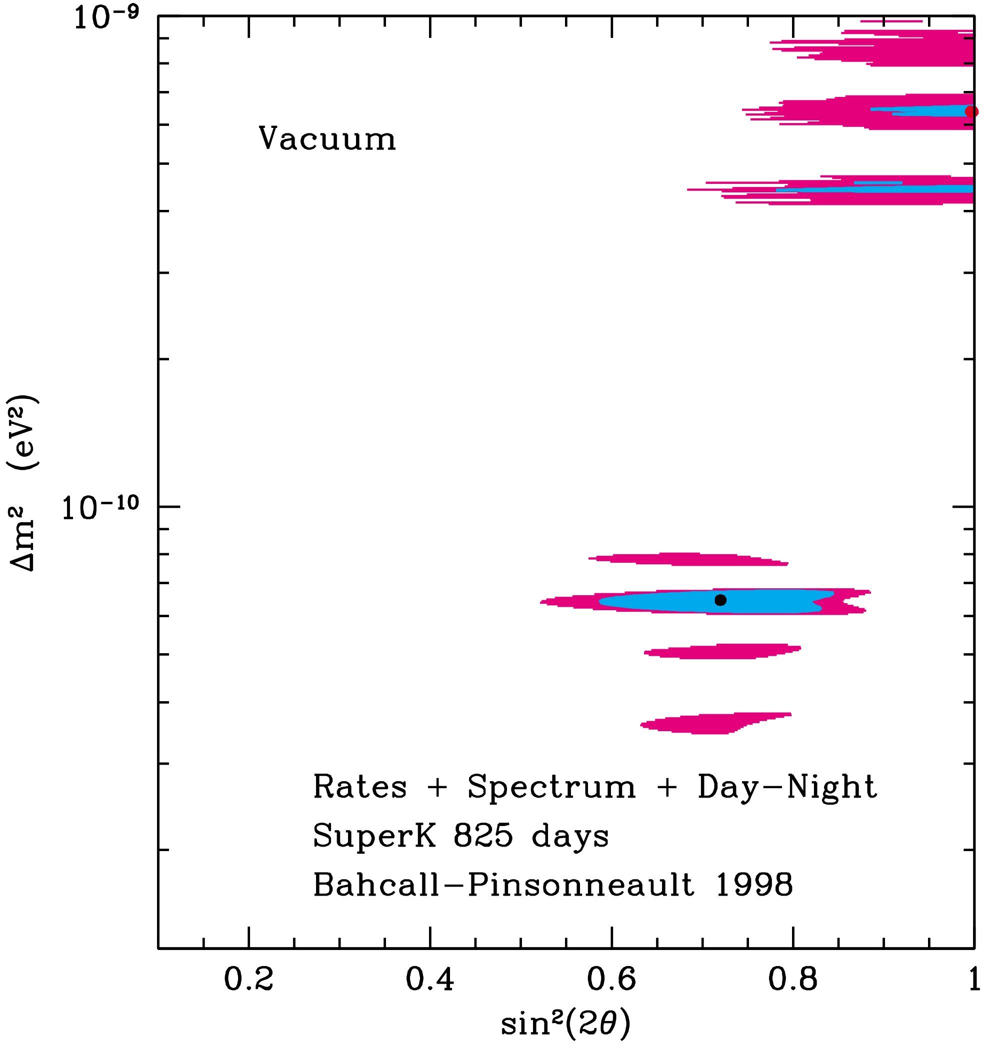
1 SNU≡1 evt/s per 10^{36} target atoms

Expected production:
1.5 Ar nuclei/day

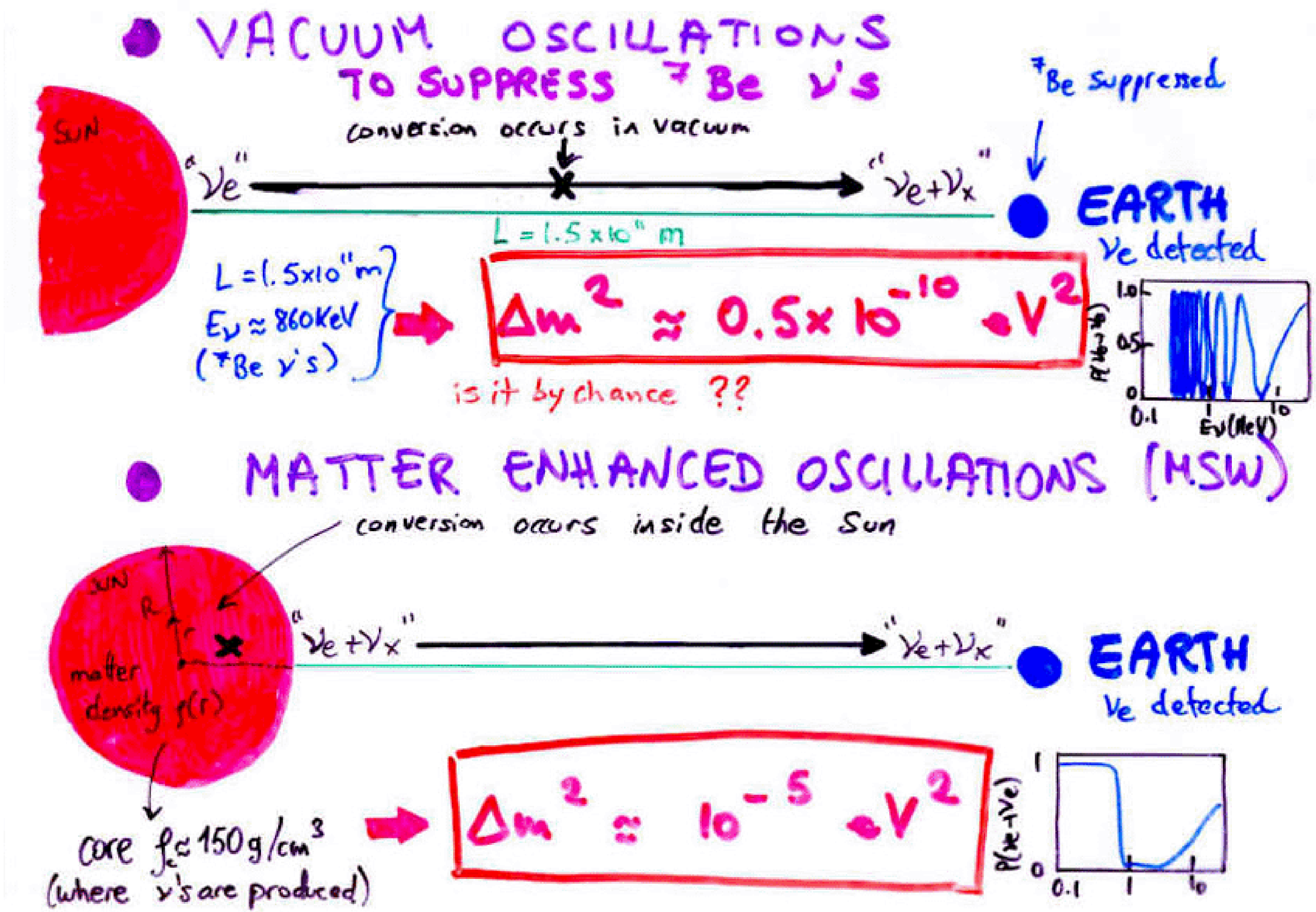
Measured rate: ***2.56–0.22 SNU***
average over 30 years!!!!

Solar deficit global solutions





Bahcall
http::/www.sns.ias.edu/~jnb


VACUUM OSCILLATIONS
TO SUPPRESS 7Be ν's
7Be suppressed
SUN
conversion occurs in vacuum
"νe"
"νe+νx"
EARTH
νe detected
L = 1.5x10" m
L = 1.5x10" m
Eν ≈ 860 KeV
(7Be ν's)
Δm² ≈ 0.5x10⁻¹⁰ eV²
is it by chance ??
1.0
0.5
0
0.1
1
10
Eν (MeV)
MATTER ENHANCED OSCILLATIONS (MSW)
conversion occurs inside the Sun
SUN
R
r
matter density ρ(r)
"νe+νx"
"νe+νx"
EARTH
νe detected
core ρc ≈ 150 g/cm³
(where ν's are produced)
Δm² ≈ 10⁻⁵ eV²
P(νe→νe)
1
0
0.1
1
10

NEUTRINO OSCILLATION IN MATTER

Mikheyev - Smirnov - Wolfenstein (MSW)

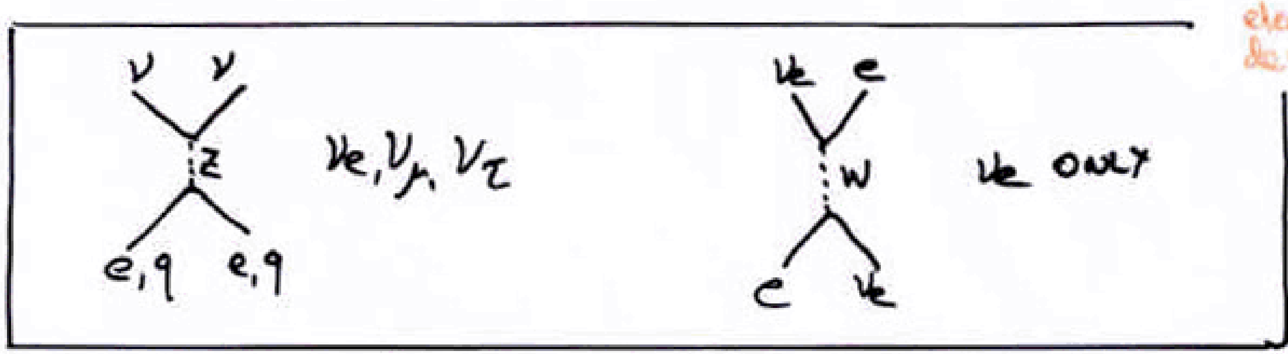
time evolution is modified to due coherent interaction with matter

$$i\frac{d\vec{\nu}}{dt} = U H^{i} U^{\dagger}\vec{\nu} + \frac{1}{2E}\begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}\vec{\nu}$$

weak eigenstates basis (↗ $\frac{d\vec{\nu}}{dt}$)

where $A \equiv 2\sqrt{2}\, G_F\, N_e\, E$

↑ N_e: electron density



for anti-neutrinos, we must replace $A \to -A$

case two neutrinos: $U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$ $H^i = \frac{1}{2E}\begin{pmatrix} m_1^2 & \\ & m_2^2 \end{pmatrix}$

$$i\frac{d\vec{\nu_i}}{dt} = \left(H^i + \frac{1}{2E}U^+\begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}U\right)\vec{\nu_i}$$
$$= \frac{1}{2E}\begin{pmatrix} m_1^2 + A\cos^2\theta & A\cos\theta\sin\theta \\ A\cos\theta\sin\theta & m_2^2 + A\sin^2\theta \end{pmatrix}\vec{\nu_i}$$

not diagonal for mass eigenstates ν_1, ν_2

mass eigenstates in vacuum $\vec{\nu_i} = \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$

→ Diagonalization

mass eigenstates in matter

$\begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix} \equiv$ mass eigenstates in matter

EFFECTIVE MASSES OF EIGENSTATES IN MATTER

$$m^2_{1,2m} = \frac{1}{2}\left[(\Sigma + A) \mp \sqrt{(A - D\cos 2\theta)^2 + D^2\sin^2 2\theta}\right]$$

$$\Sigma \equiv m_1^2 + m_2^2 \qquad D = m_2^2 - m_1^2$$

take $m_1^2 \approx 0$ $m_2^2 > 0 \Rightarrow$ $\boxed{\Sigma \approx D \approx m_2^2}$

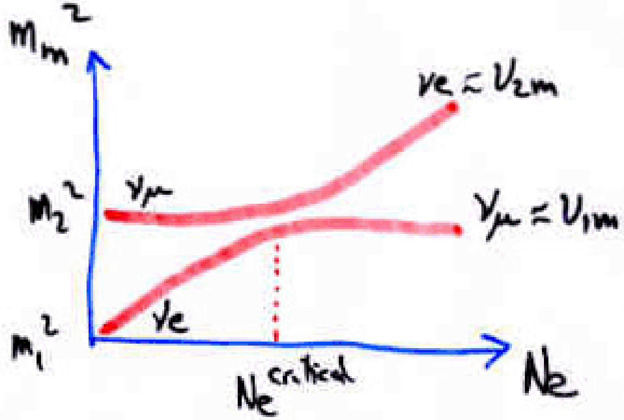
take θ small

$\underline{A=0}$: $\nu_{1m} \approx \nu_1 \approx \nu_e$

$\nu_{2m} = \nu_2 \approx \nu_\mu$

$\underline{A \to \infty}$: $\nu_{1m} \approx -\nu_\mu$

$\nu_{2m} \approx \nu_e$

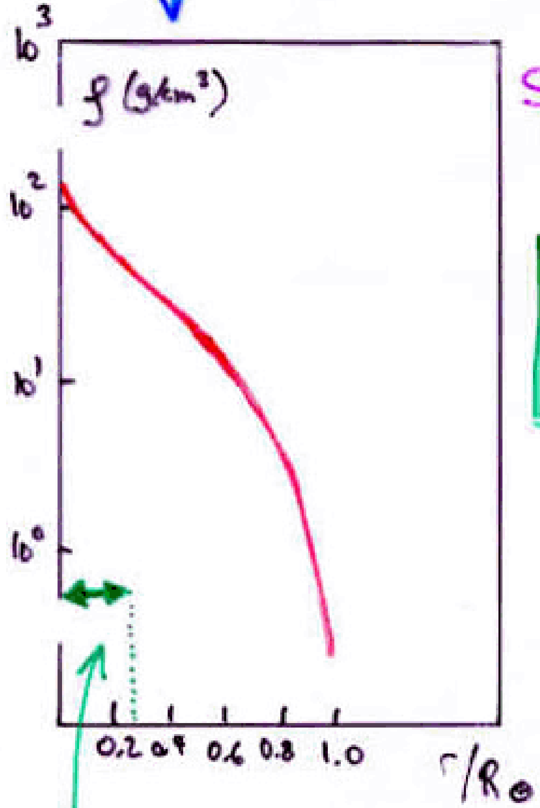


$$Ne^{critical} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}\, G_F\, E_\nu}$$

WHEN THE NEUTRINOS TRAVEL FROM THEIR PRODUCTION RADIUS (CORE) TOWARDS THE SURFACE, THEY TRAVERSE REGIONS OF DIFFERENT DENSITIES

WHEN $N_e(r) \approx N_e^{critical} \equiv \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F E_\nu}$

⇒ RESONANCE



SOLAR DENSITY VERSUS RADIUS

region where neutrinos are produced (core)

SINCE $N_e(r) \searrow$ $r \nearrow$
A CONDITION FOR RESONANCE IS

$N_e(r = r_{creation}) > N_e^{critical}$

$\Rightarrow \cos 2\theta < \frac{2\sqrt{2} G_F E_\nu N_e^{creation}}{\Delta m^2}$

RESONANT:

$\Rightarrow$ $\Delta m^2 \cos 2\theta < E_\nu \times C$

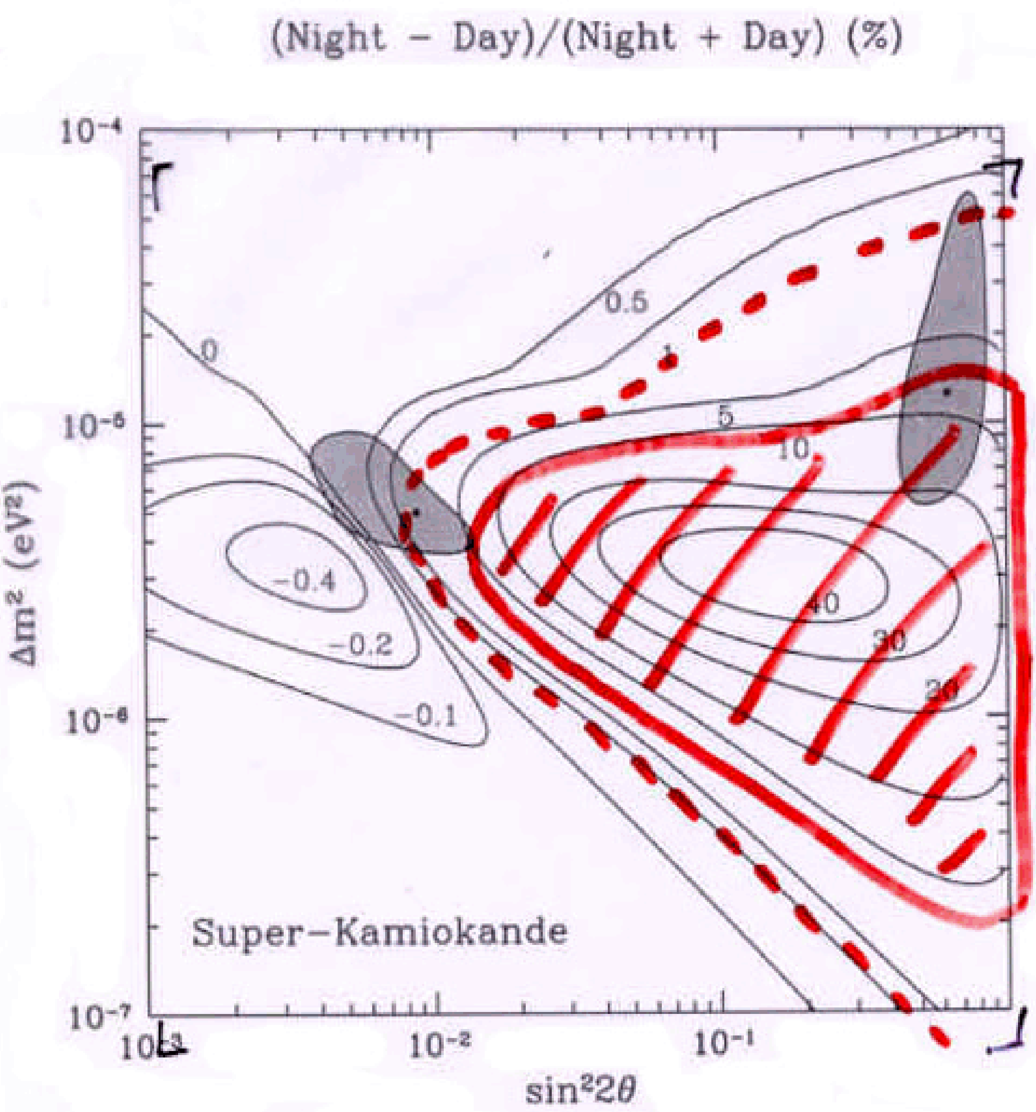
$C \equiv 2\sqrt{2} G_F N_e^{creation}$

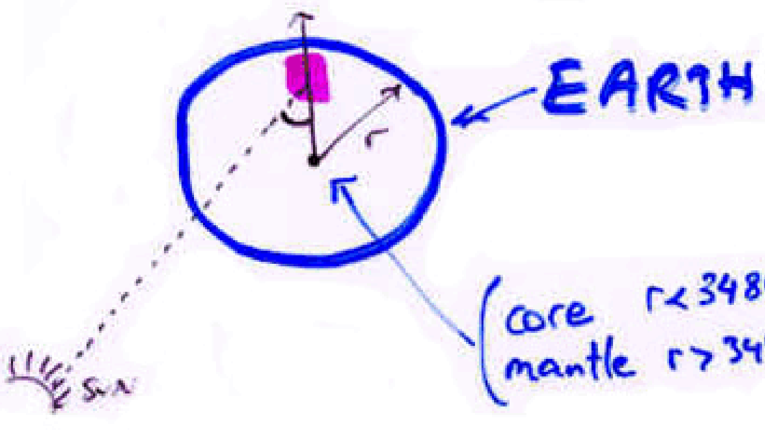
regions Δm^2, $\sin^2 2\theta$ where resonance occurs (and E_ν dependent)

⇒ **ENERGY DEPENDENT SUPPRESSION**

MSW REGENERATION IN EARTH

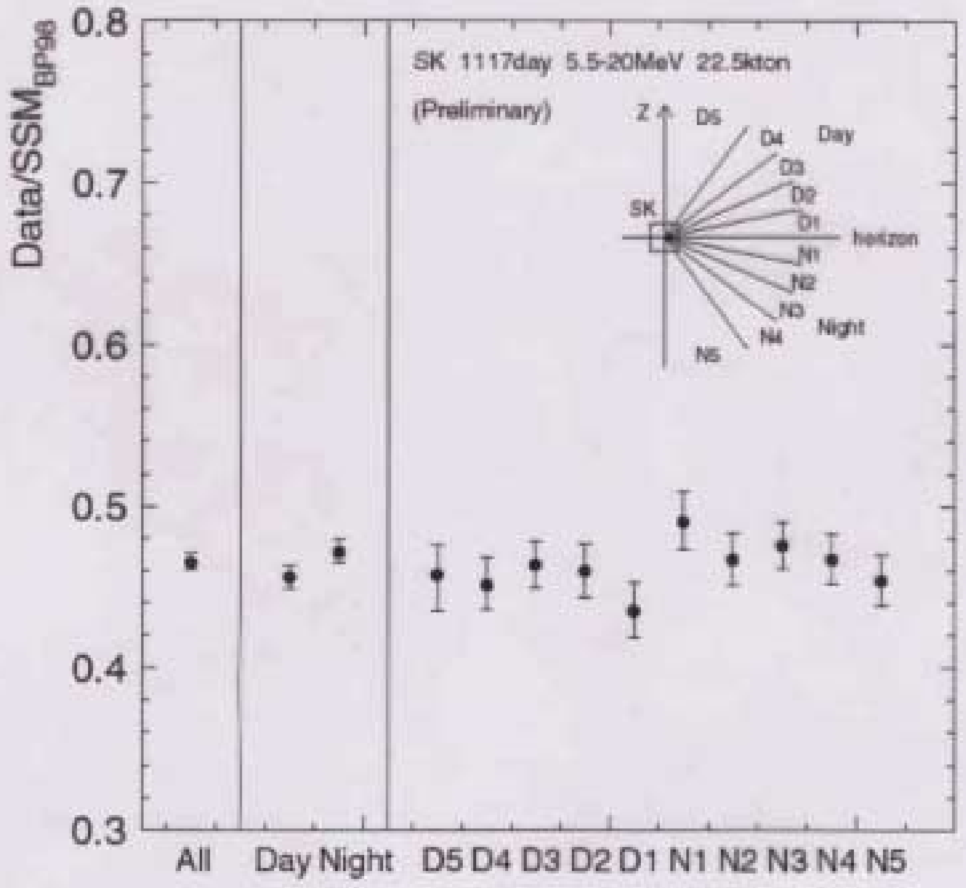
Bahcall, Krastev, may '97





(core r < 3480 km $\rho \sim 5-12\ g/cm^3$
mantle r > 3480 km $\rho \sim 1-5\ g/cm^3$)

Day/Night Flux difference



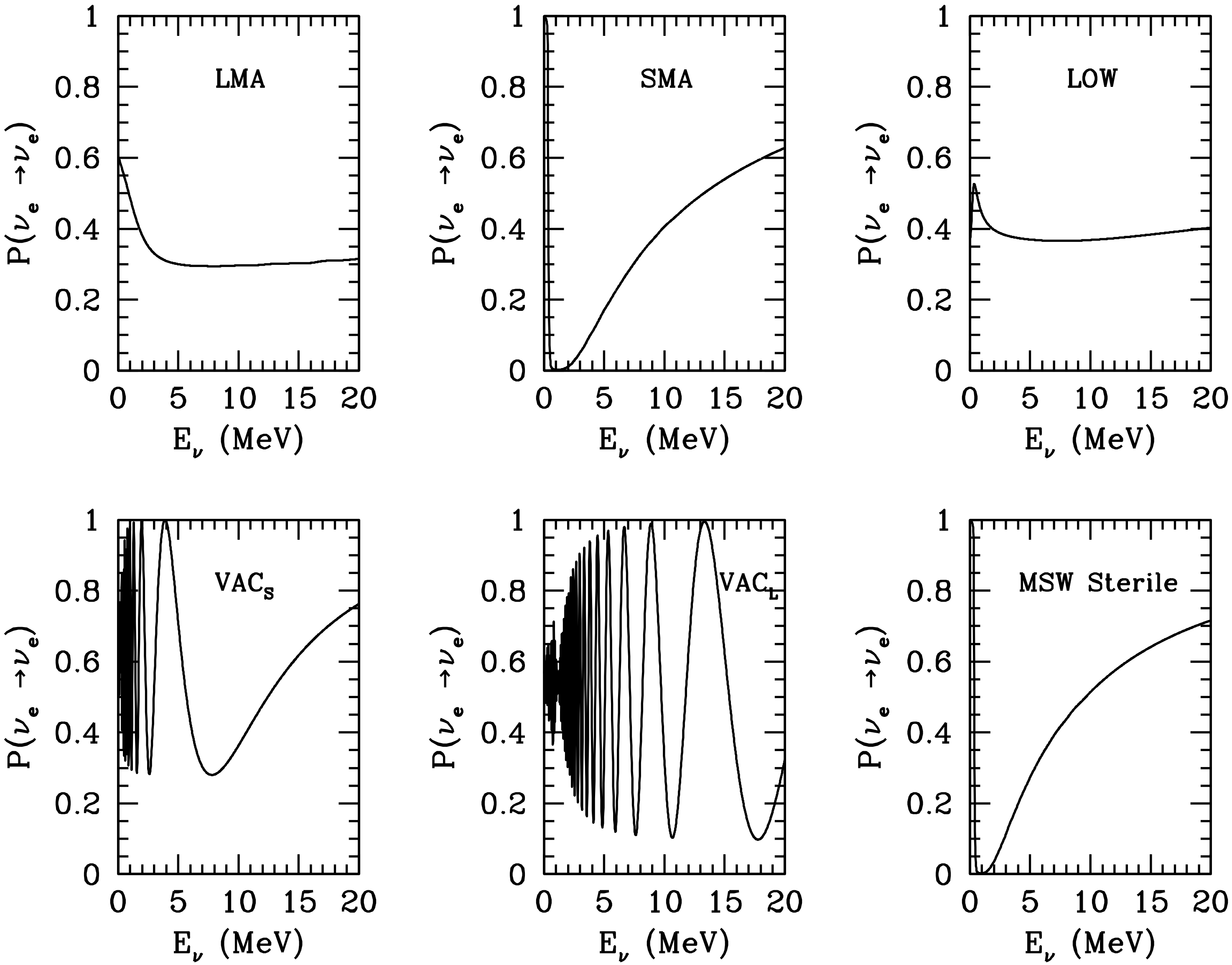
Day = 2.35 $\pm$ 0.04(stat.) $\pm^{0.08}_{0.07}$(syst.) x10^6/cm^2/s

Night = 2.43 $\pm$ 0.04(stat.) $\pm^{0.08}_{0.07}$ (syst.) x10^6/cm^2/s

$$\frac{D-N}{(D+N)/2} = -0.034 \pm 0.022(\text{stat.})^{+0.013}_{-0.012}\ (\text{syst.})$$

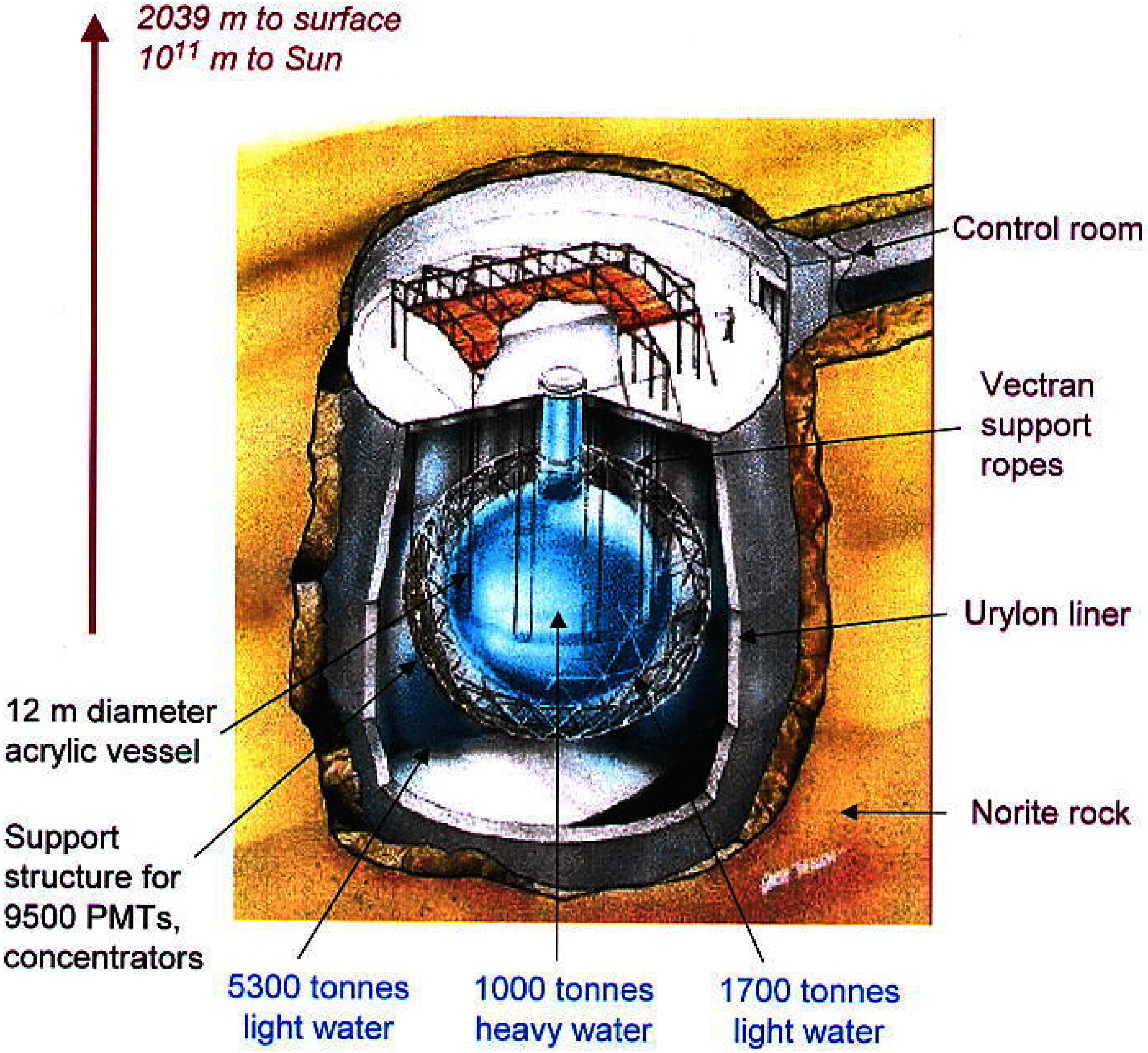
1.3 σ level → not strong yet

Solar neutrino survival probabilities



Bahcall
http::/www.sns.ias.edu/~jnb

The SNO Detector



- **Location:** 6800 ft. level of INCO's Creighton mine near Sudbury, ON, Canada (~70 muons / day)
- **SNO Detector:** $9438_{\text{inward}} + 91_{\text{outward}}$ Hamamatsu 8" PMTs + concentrators = 59% coverage

SNO Measurements

Charged Current Reaction (D_2O):

CC $\nu_e + d \rightarrow p + p + e^-$ $E_{thres} = 1.4$ MeV (only ν_e)

- ν_e energy spectrum (distortion MSW effect)
- Some directional sensitivity ($1 - 1/3 \cos\theta_e$)

Neutral Current Reaction (D_2O):

NC $\nu_x + d \rightarrow \nu_x + p + n$ $E_{thres} = 2.2$ MeV (ALL ν types)

- Total solar ^8B neutrino flux (active neutrinos)

$$\text{Ratio} = \frac{CC}{NC} = \frac{(\nu_e)\ \text{flux}}{(\nu_e + \nu_\mu + \nu_\tau)\ \text{flux}}$$

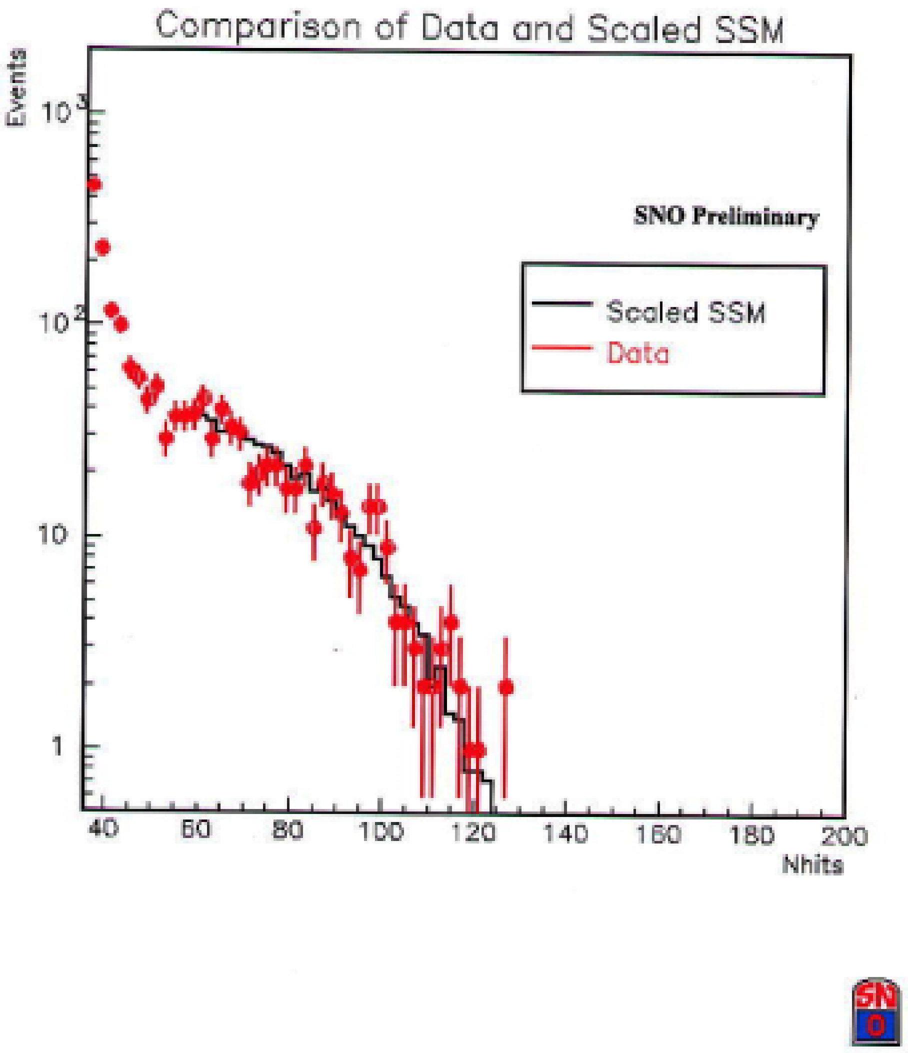
Elastic Scattering Reaction (D_2O,H_2O):

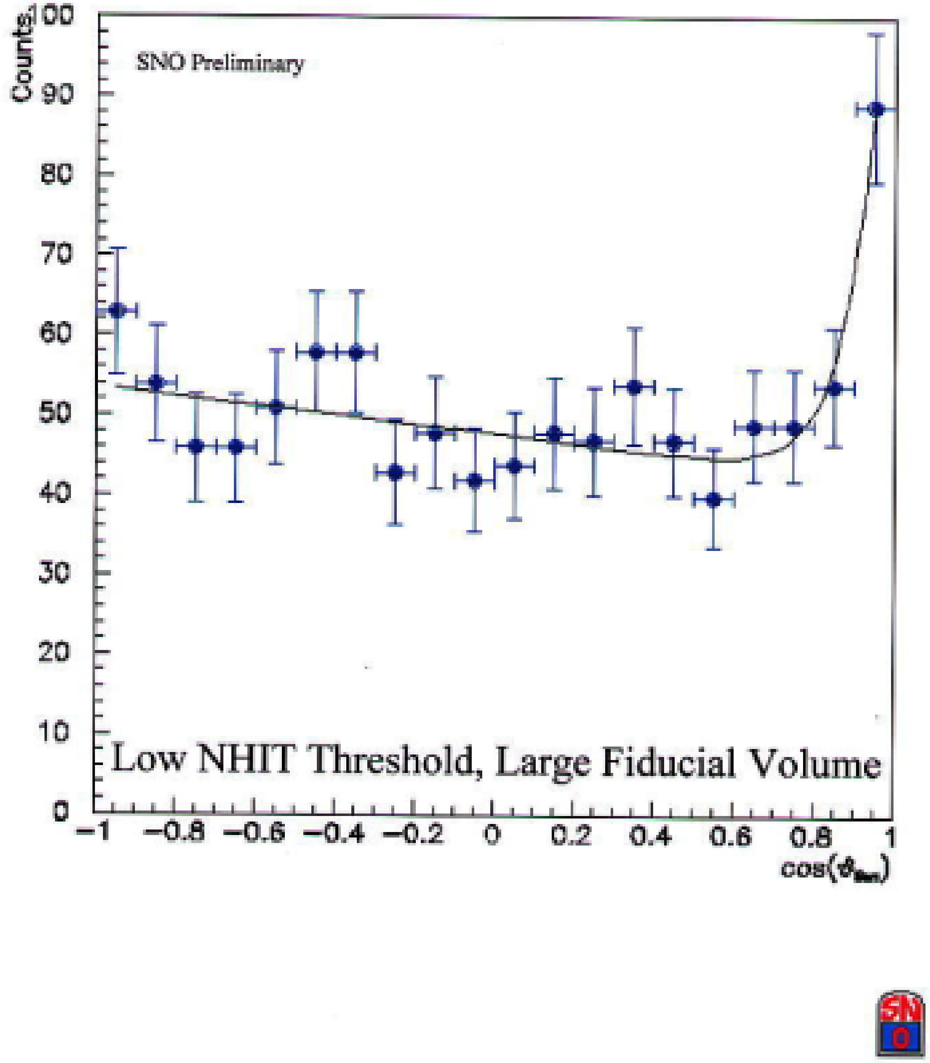
ES $\nu_x + e^- \rightarrow \nu_x + e^-$ $E_{thres} = 0$ MeV (mostly ν_e)

- Low counting rate
- Directional sensitivity (very forward peaked)

$$\text{Ratio} = \frac{CC}{ES} = \frac{(\nu_e)\ \text{flux}}{0.86\ \nu_e + 0.14(\nu_\mu + \nu_\tau)\ \text{flux}}$$

SNO preliminary data





BOREXINO

Gran Sasso, Italy

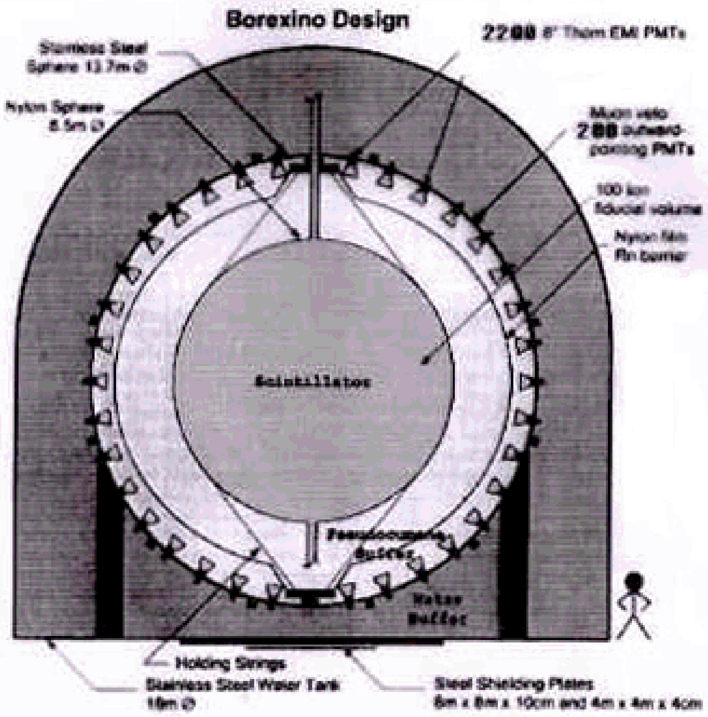
Real time experiment based on ν–e scattering

Interest focused in the ^{7}Be monochromatic line (863 KeV) and its time (day-night, seasonal) variation

Detection threshold 250 KeV ➔ 46 evts/day in the 100 tons fiducial volume expected according to SSM

Extremely sensitive to radio impurites → Background level:

aim at 10^{-16} g of ^{238}U/g



300 tonnes of ultra-pure scintillator viewed by 2200 PMT

Outer ultra-pure water shield (2400 tonnes) viewed by 200 PMT

SMA ⇒ full suppession
LMA ⇒ half suppression

VO ⇒ seasonal variation

(≥ 2001)

Solar neutrinos detection in ICARUS

- Two reactions can be measured independently:

Elastic scattering on atomic electron

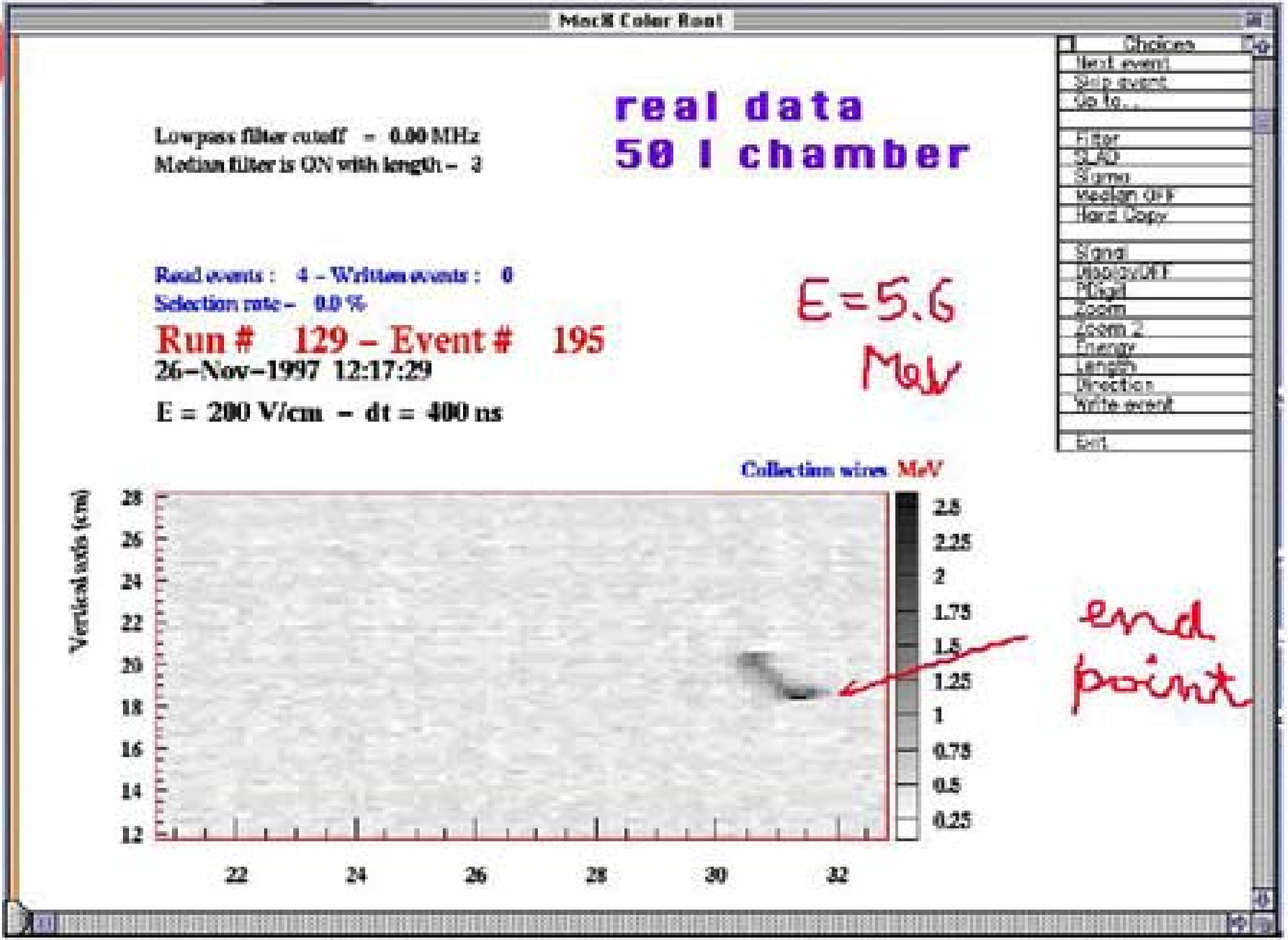
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

ν absorption on Argon nuclei

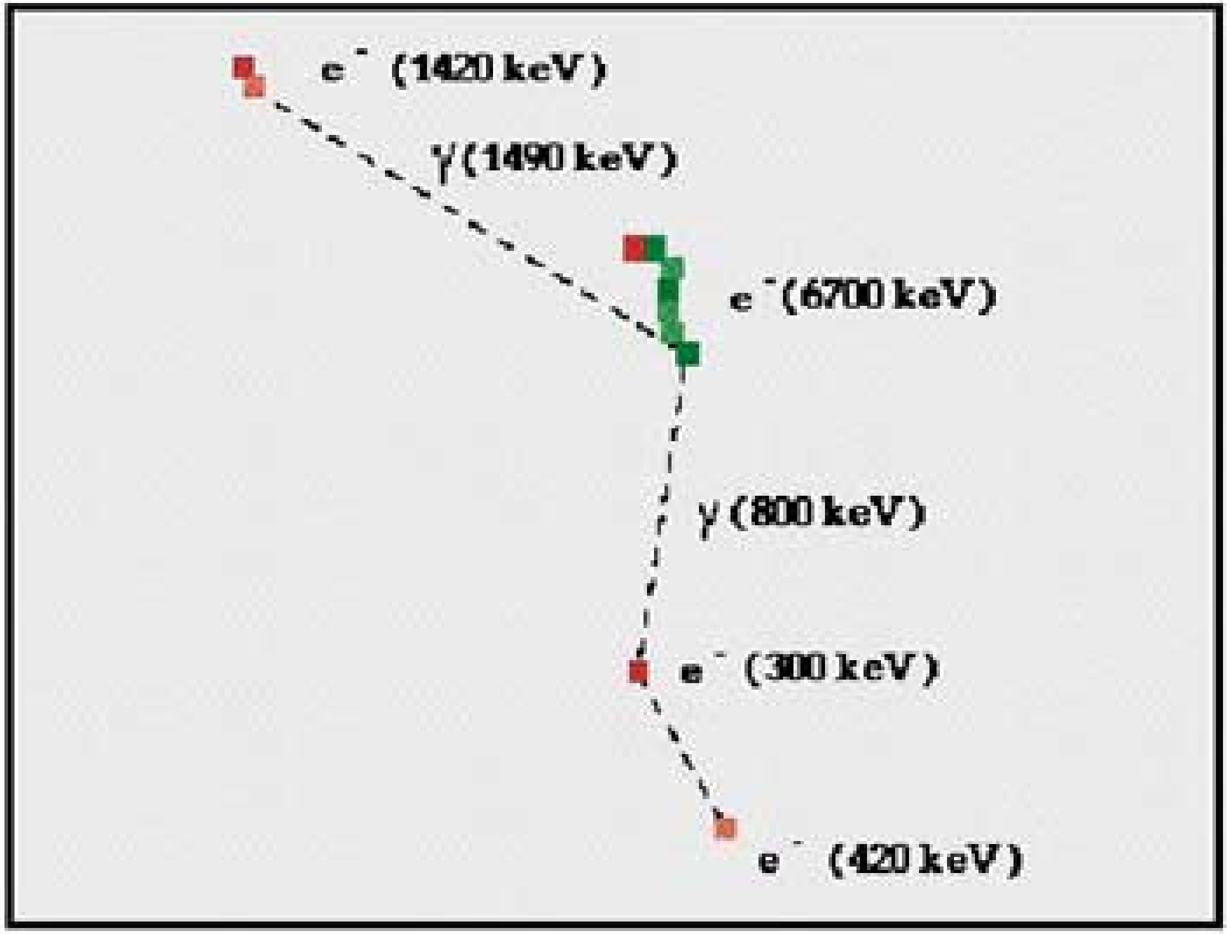
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

- **Signature**:
  - Primary electron track
  - Absorption: surrounded by low energy secondary tracks ($^{40}K^*$ de-excitation).
- Prototype setup: electron track visible down to kinetic T=150 KeV
- Electron track threshold = 5 MeV (needed to reduce background contribution and to establish the e⁻ direction in elastic scattering).
- Sensitive to ^8B component of the solar spectrum.

Radioactive source: 6 MeV γ's



Typical Montecarlo Gamow -Teller digitised event



$E_{\text{main electron}}$ = 6700 keV

Associated compton energy = 2140 keV

Multiplicity = 3

Solar neutrino rates and sensitivity

470 ton fiducial, all cuts imposed

Events/year

Elastic channel	212
Background	6
Absorption channels	759
Background	26

Events per year for a 600 ton detector	
Te (MeV)	**Neutrons**
0.0	7400
1.0	3404
2.0	1554
3.0	696
4.0	318
5.0	144
6.0	66
7.0	30
8.0	13

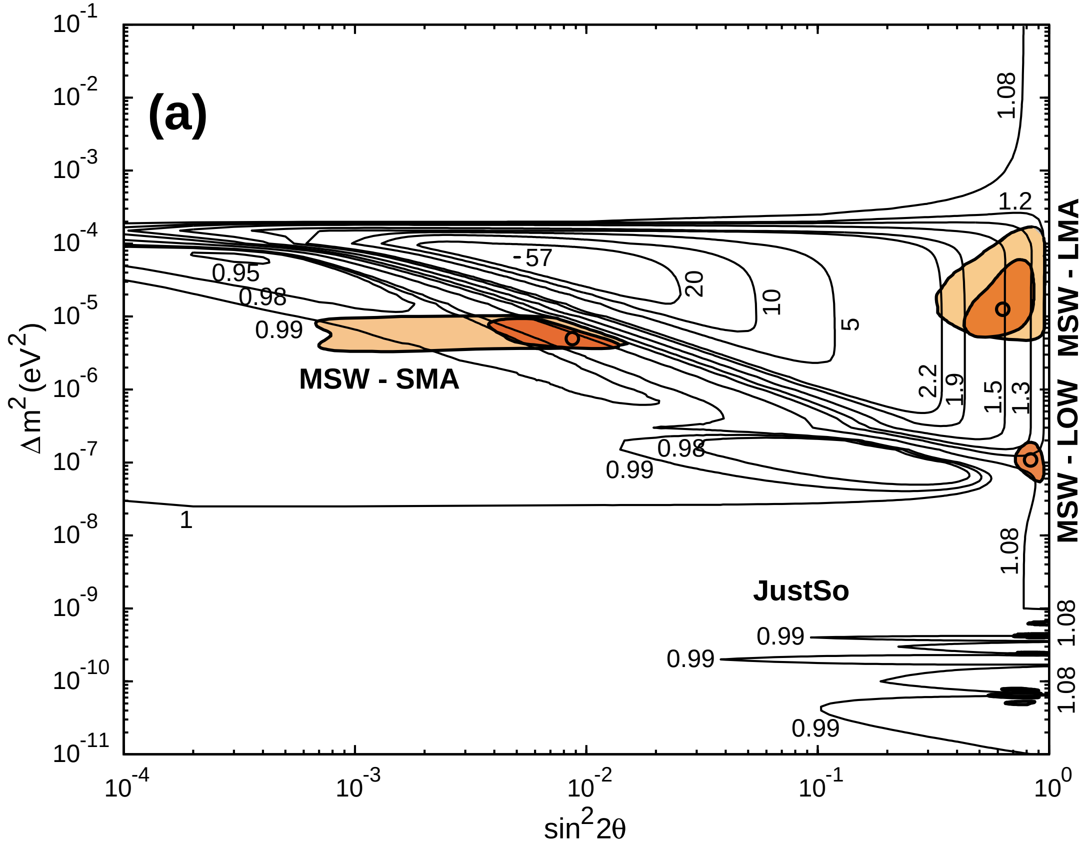
$$R \equiv \frac{N^{ES} / N^{ES}_{theory}}{N^{ABS} / N^{ABS}_{theory}}$$

ES=elastic scattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

ABS=absorption events

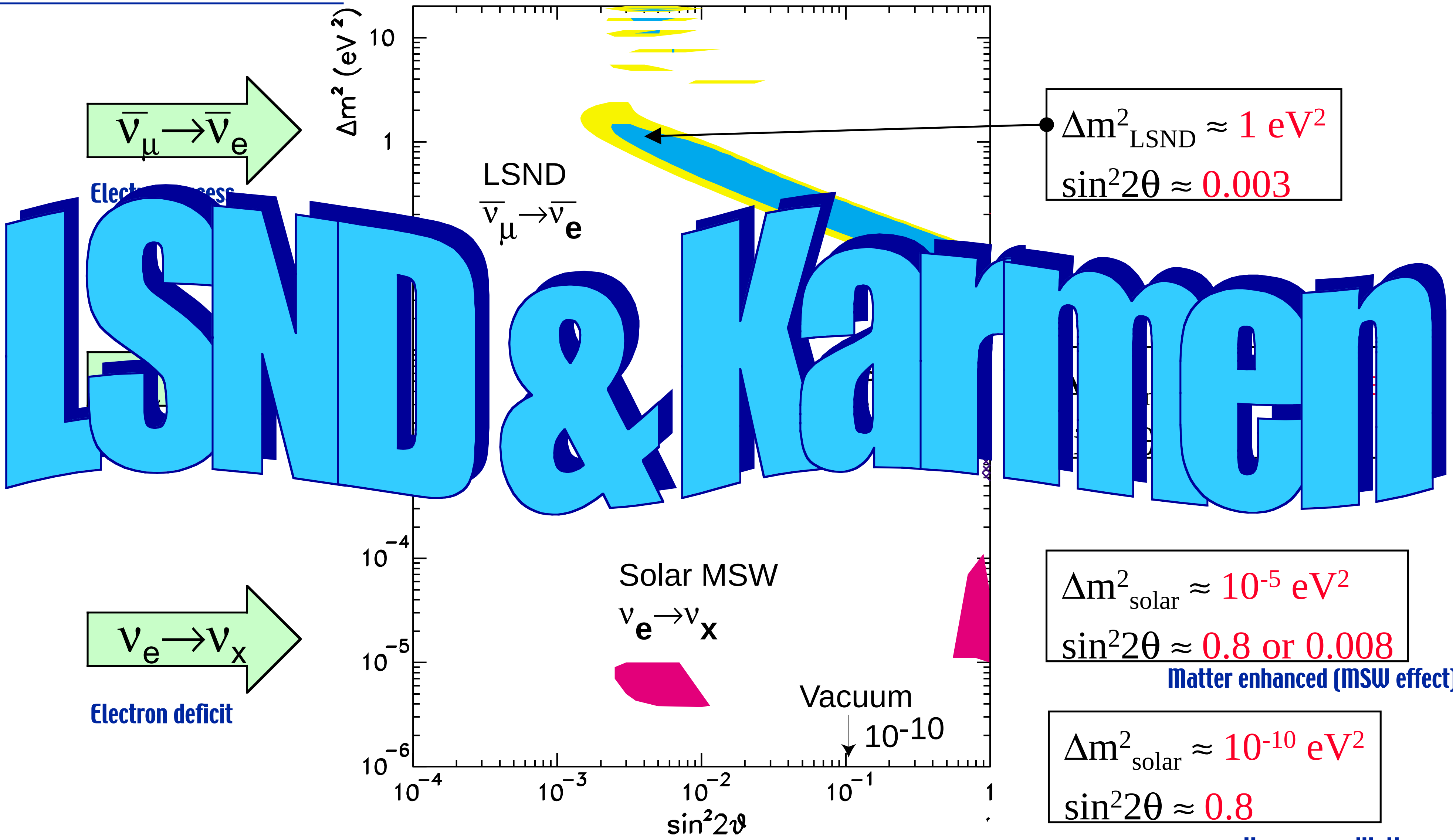
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$



$$\Delta R / R \approx 7\%(1kt \times yr),\ \ 5\%(2kt \times yr),\ \ 4\%(4kt \times yr)$$

Oscillation map - “allowed regions”

Two-neutrino oscillation



$\Delta m^2_{LSND} \approx 1\ eV^2$
$\sin^2 2\theta \approx 0.003$

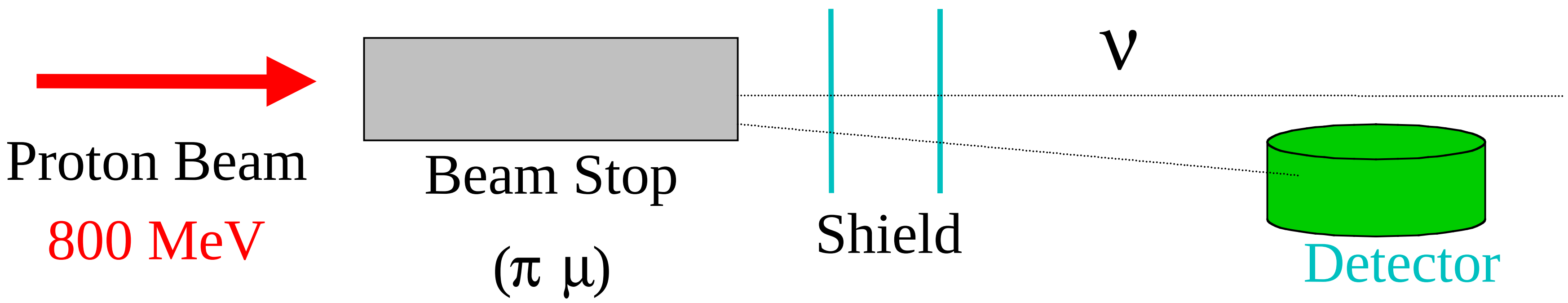
$\Delta m^2_{solar} \approx 10^{-5}\ eV^2$
$\sin^2 2\theta \approx 0.8$ or 0.008

Matter enhanced (MSW effect)

$\Delta m^2_{solar} \approx 10^{-10}\ eV^2$
$\sin^2 2\theta \approx 0.8$

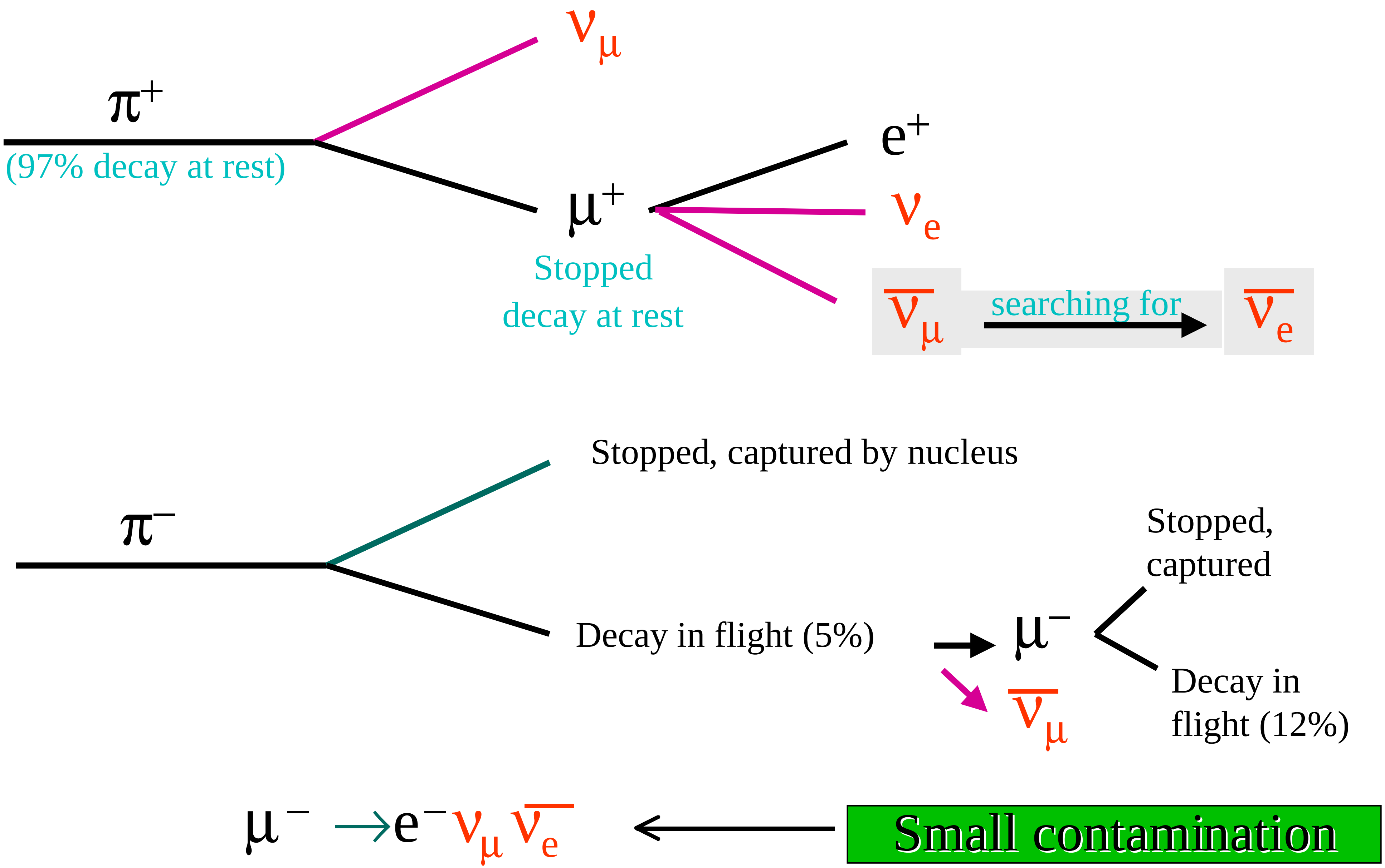
Vacuum oscillation

Medium Energy Accelerator



Detector	LSND (U.S.A.)	KARMEN (U.K.)
Accelerator	LAMPF	ISIS
Proton Current	1 mA	0.2 mA
Beam Pulse	500 μs	2 x 100μs
	8.3 ms pause	20 ms pause
Mass	180 tons	56 tons
Distance	17 m	30 m
Angle with beam	17^0	90^0

Neutrinos produced from π and μ decays



Search for oscillations at medium energy

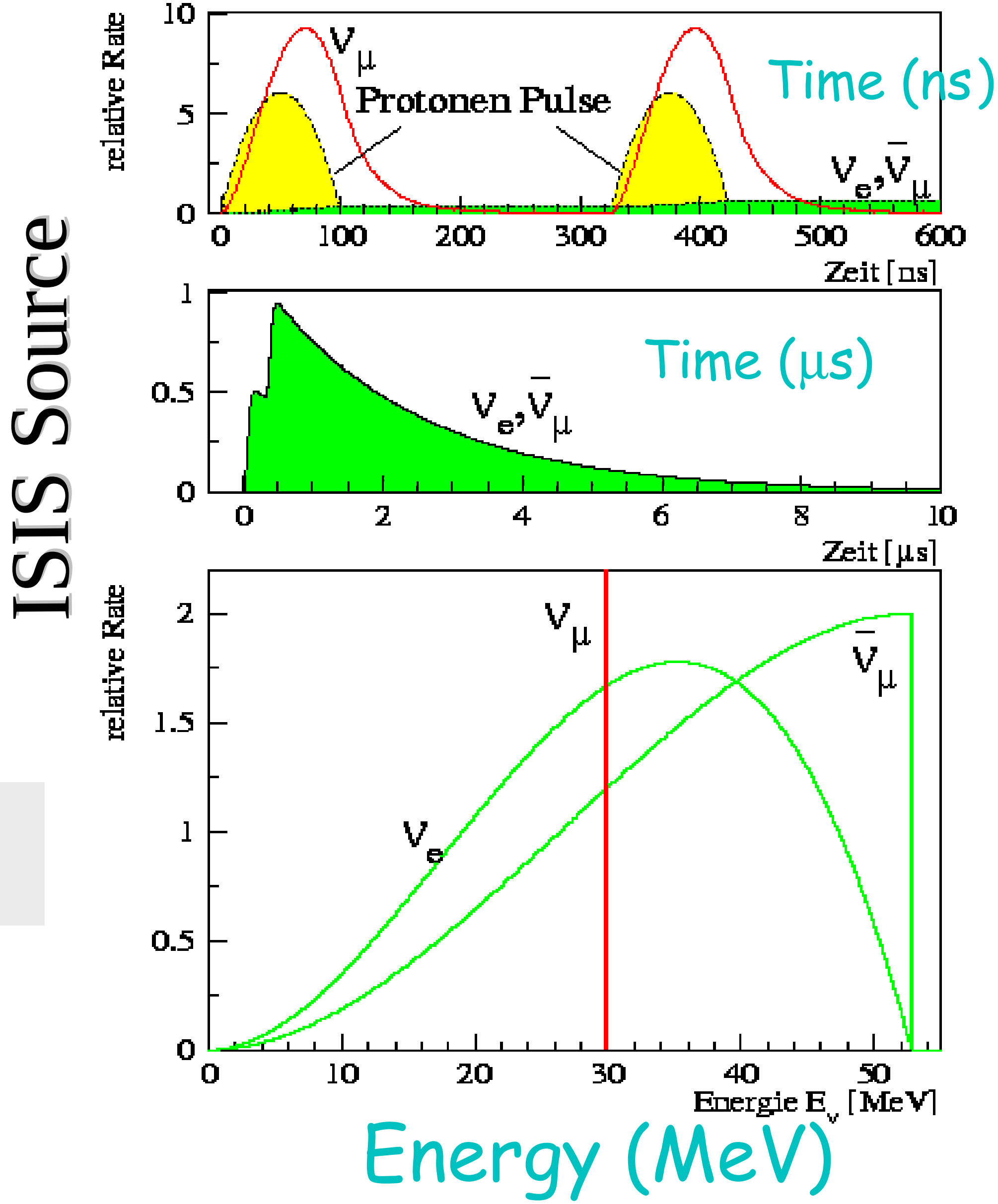
Neutrinos mainly produced from decay at rest (DAR) of π and μ

Also from decay in flight (DIF) of these particles

Mainly looking for $\bar{\nu}_e$ appearance

$\bar{\nu}_e / \nu_\mu$ (DAR) $= 4 \times 10^{-4}$

☆ *At ISIS, time separation of π and μ decays*



LSND (Liquid Scintillator Neutrino Detector)

Cylindrical Tank 8.3 m long, 5.7 m in diameter

1220 8-inches PMT Filled with mineral oil (C_nH_{2n+2}) + small admixture of b -PBD

Dectects scintillation

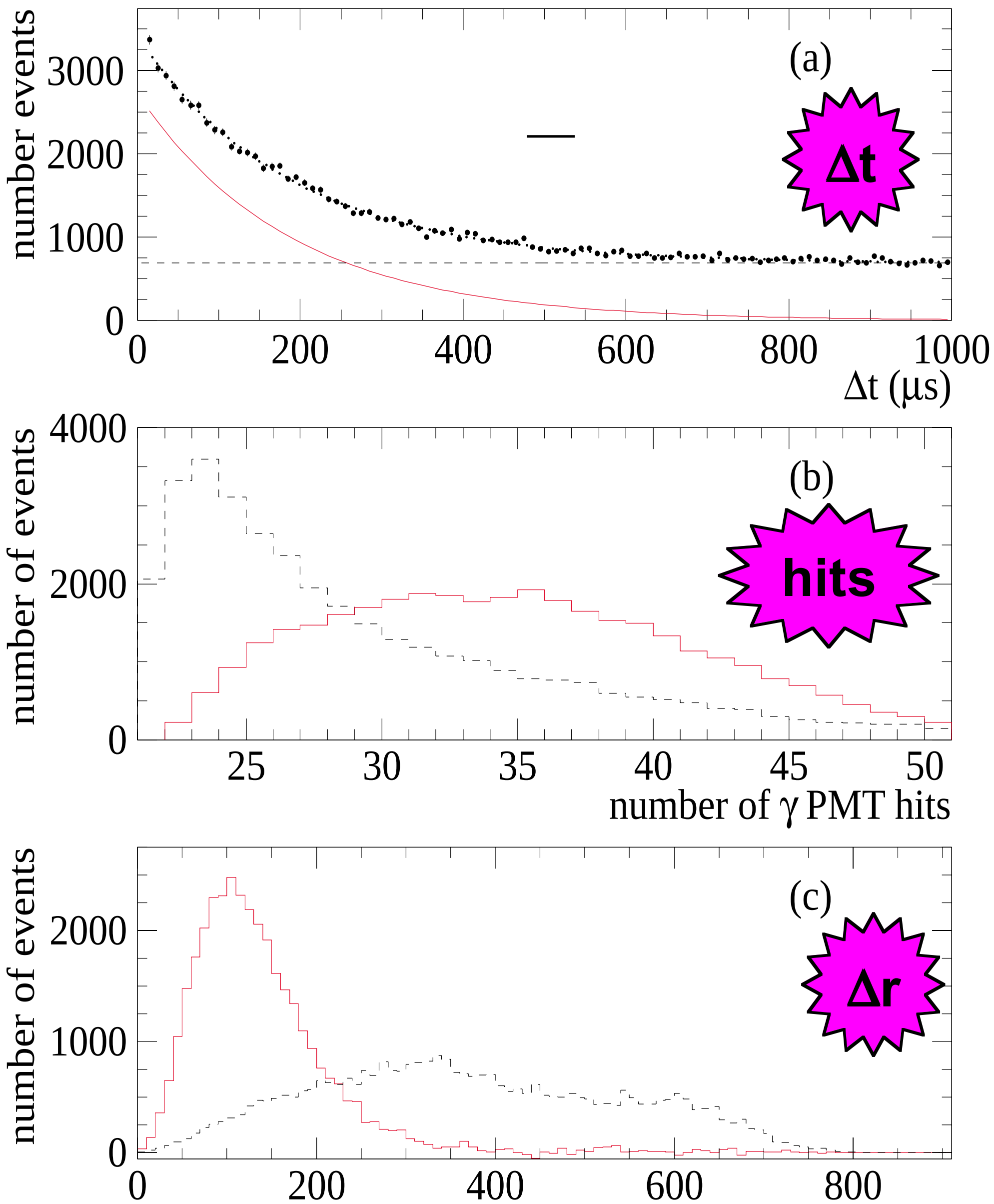
and Cerenkov light

Energy resolution ~ 7% at ~50 MeV

Angular resolution ~12^0

Position resolution ~30 cm

$\nu_\mu \to \nu_e$ *search in LSND*



Signature:

$$\bar{\nu}_e + p \to e^+ + n$$

prompt positron signal, energy range

$$n + p \to d + \gamma(2.2\ \text{MeV})$$

delayed correlated photon

❶ **Particle identification (PID):**

(Cerenkov light)

ε ˉ 80%; neutron rejection ˉ 10 3

❷ **Signature discrimination:**

From the p.d.f., build likelihood function:

$$L = P(\Delta t) x P(\Delta r) x P(hits)$$

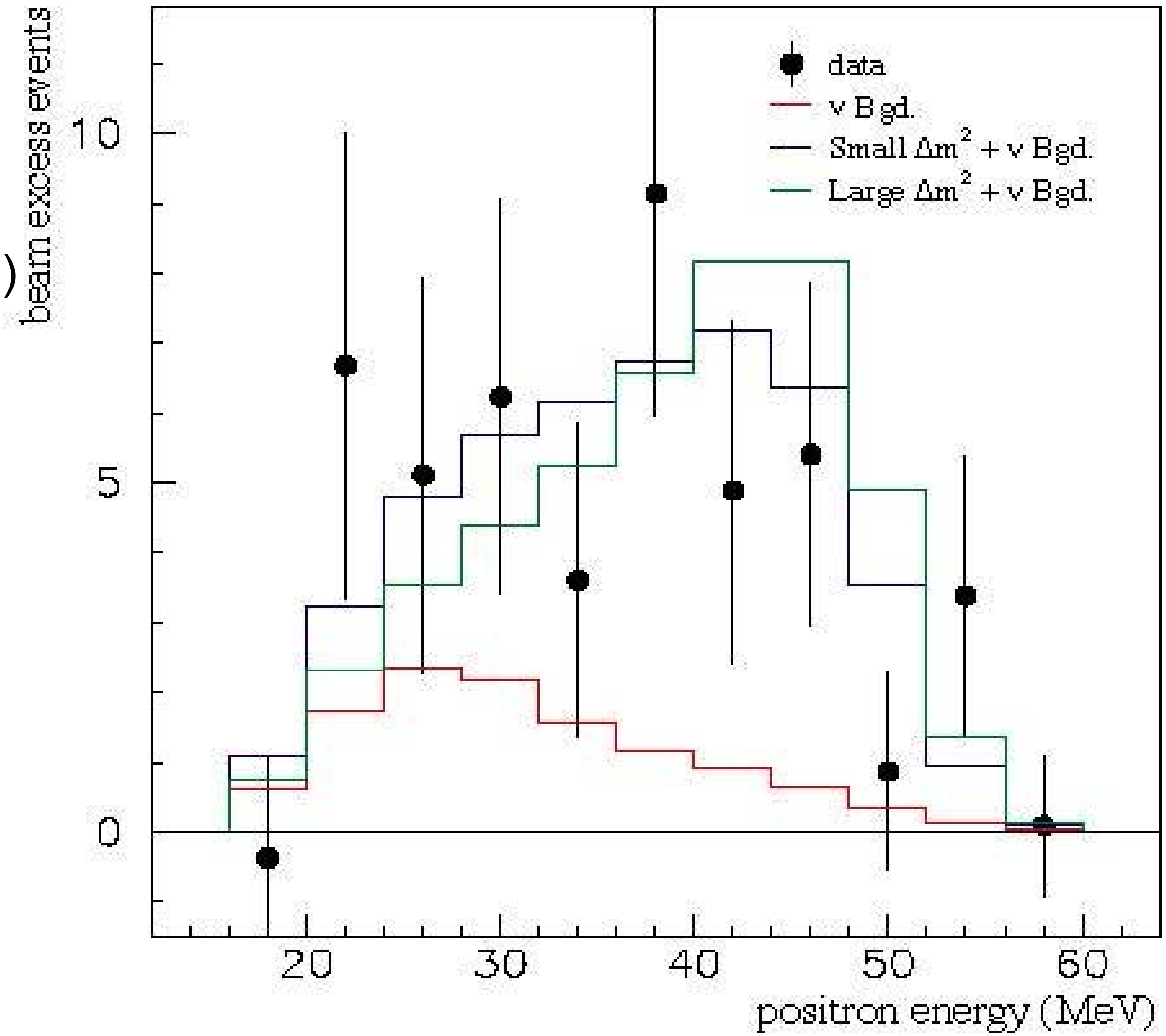
$$R = \frac{L(correlated)}{L(accidental)}$$

LSND DAR Oscillation Search

36 < Ee < 60 MeV, R>30:

(R>30: $\varepsilon_{correlated}$=23%, $\varepsilon_{accidental}$=0.6%)

¥Signal: 22 events
¥Beam unrelated: 2.5–04
¥Beam related: 2.1–0.4
¥Excess: 17.4–4.7 events
¥Prob stat. ˉ 4x10 —8



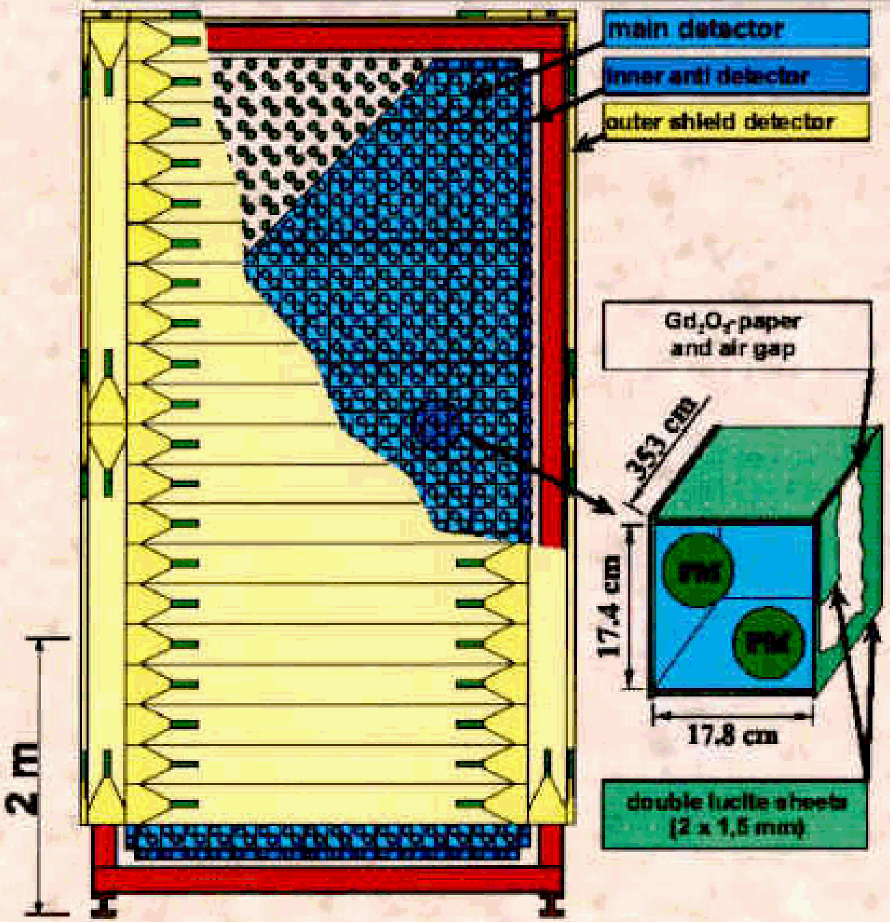
LSND

Preliminary 96 - 97 & Total

Selection	Beam On	Beam Off	ν Background	Total Excess
R > 30 $20<E_\nu<60$	61	15.6 ± 1.0	11.5 ± 1.5	33.9 ± 8.0
R > 30 $36<E_\nu<60$	29	5.2 ± 0.6	3.0 ± 0.6	20.8 ± 5.4

Data Sample	Fitted Excess	Total Excess	Oscillation Probability %
1993 - 1995	63.5 ± 20.0	51.0 ± 20.2	0.31 ± 0.12 ± 0.05
1995 - 1997	35.1 ± 14.7	30.3 ± 14.8	0.32 ± 0.15 ± 0.05
1993 - 1997	100.1 ± 23.4	82.8 ± 23.7	0.31 ± 0.09 ± 0.05

KARMEN



6 x 3.5 x 3.2 meters

Filled with 65000 l of liquid scintillator

2048 3-inches PMT

Detects scintillation light

neutron capture in Gd

Energy resolution

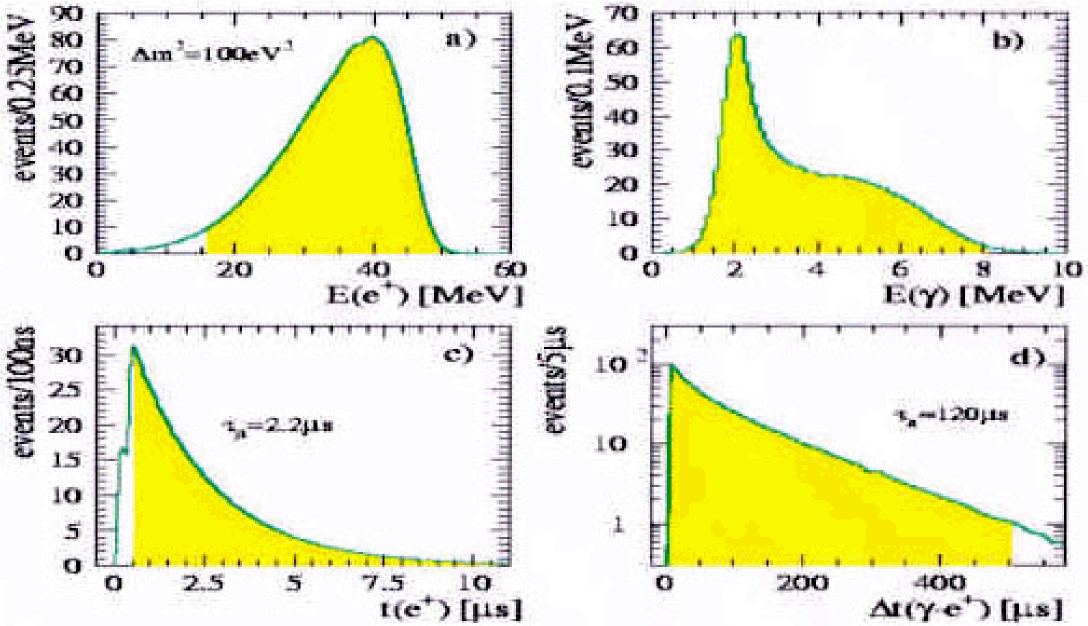
$\sim 11.5\% / \sqrt{E(MeV)}$

Time resolution ~ 2 ns

Position resolution ~ 6 cm

KARMEN SIGNAL

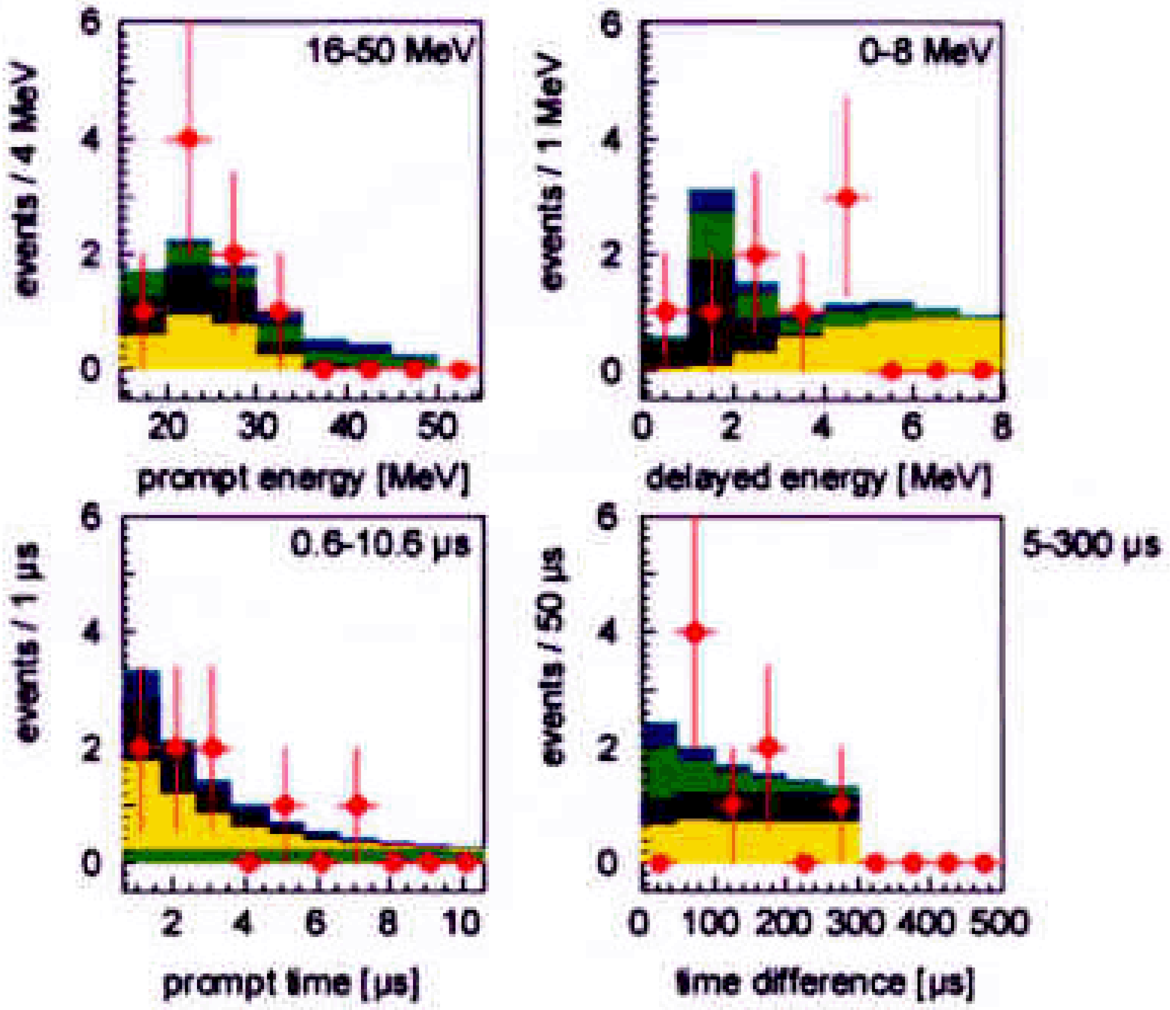
Positron Energy — Photon Energy



Event time — Time correlation between e and γ

Neutrino Oscillation Search: *Sequential Signatures*

final step: *veto information is used, optimised cuts*



8 events measured

(7.8 ± 0.5) events expected

■ (green)	cosmic background	:	1.9 ± 0.1 events
■ (yellow)	seq. ν_e-^{12}C reactions	:	2.6 ± 0.3 events
■ (black)	rand. ν_e-^{12}C + backgr.	:	2.3 ± 0.3 events
■ (blue)	intrins. contamination	:	1.1 ± 0.1 events

Likelihood Analysis

prompt event :	visible energy	16 - 50 MeV
	time	0.6 - 10.6 μs
delayed event :	visible energy	0 - 8 MeV
	time difference	5 - 300 μs
	position correlation	$\Delta x < 80$ cm

+ no activity in any of 3 veto systems

data taking	Feb. 97 - Feb. 99
protons on target	4670 C

total background	7.82 ± 0.74
measured sequences	8

signal excluded by LH analysis	> 3.4 (90% CL)
expect. oscillations (max. mixing)	1604 ± 176

KARMEN2 Oscillation Limit

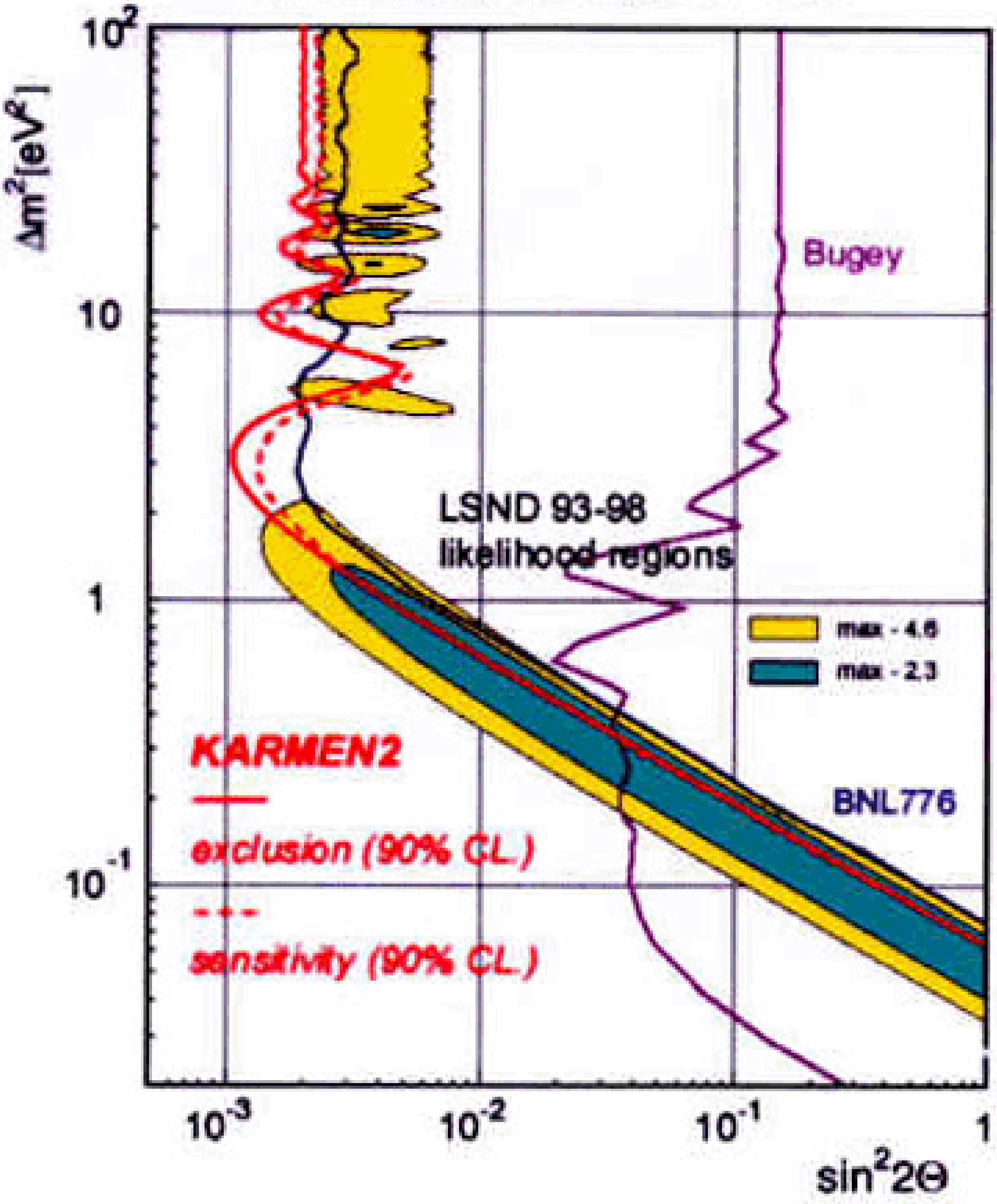
$\sin^2 2\theta < 2.1 \times 10^{-3}$ (90% CL.)

large Δm^2

Unified approach

KARMEN2 oscillation limit

2 years data taking 2/97-2/99



$\sin^2 2\theta < 2.1 \times 10^{-3}$ (90% CL.)

unified approach : R. D. Cousins, G.J. Feldman
Phys. Rev. D 57 (1998) 3873

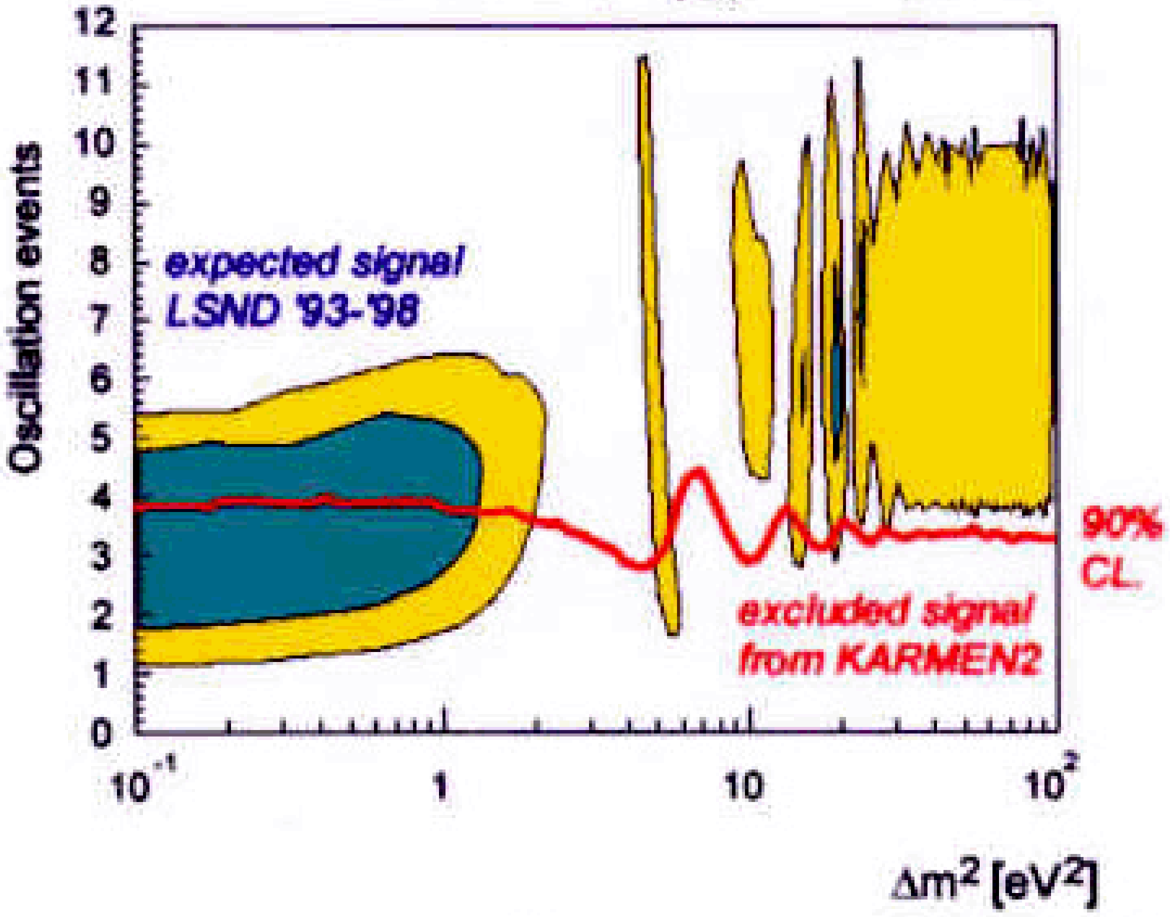
KARMEN2 oscillation analysis :

new event based likelihood method

correlated $E(e^+)$ $t(e^+)$ $E(\gamma)$ $\Delta t(\gamma)$ $\Delta r(\gamma)$

+ poisson distrib. background (N_{ev})

→ null result (N_{osc} = 0 !)



limit for small Δm^2	limit for large Δm^2
$N_{osc.}$ < 4.0 events	$N_{osc.}$ < 3.4 events

(90% confidence interval in unified approach)

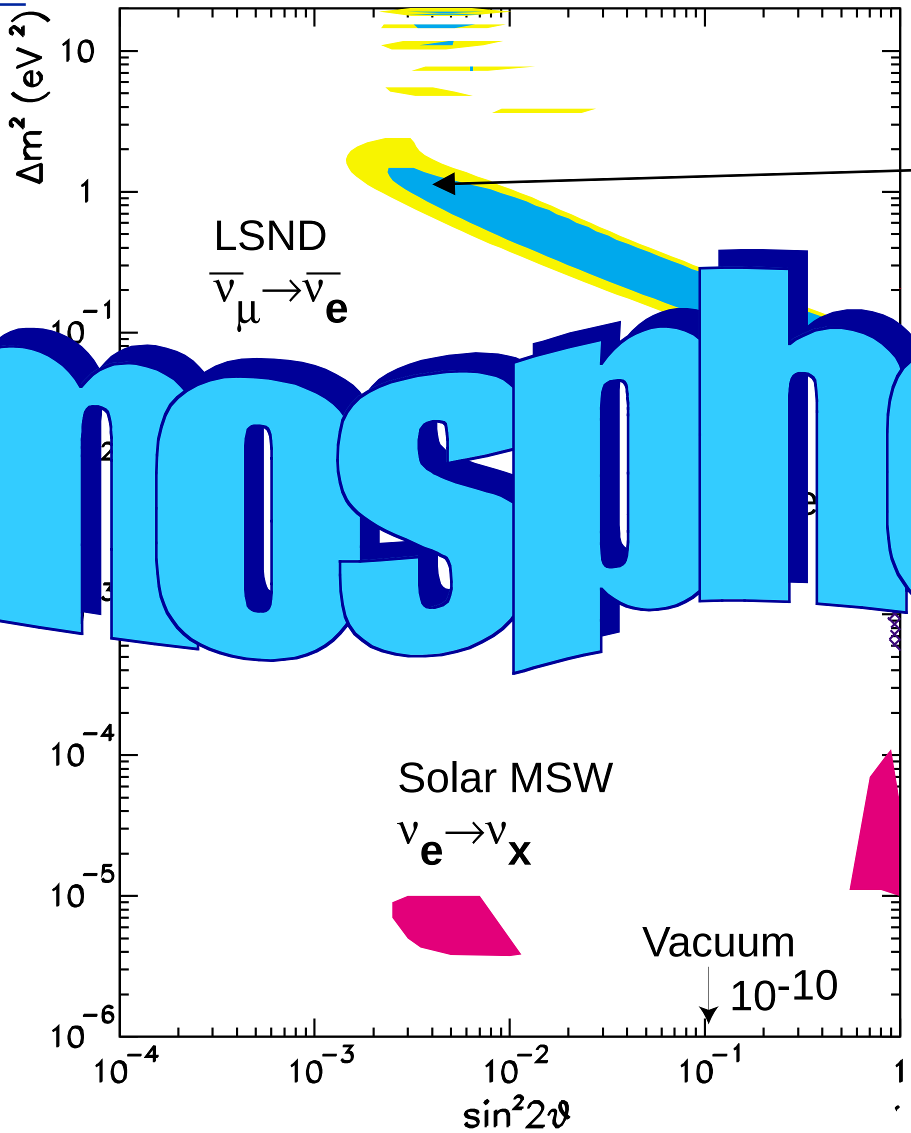
Oscillation map - “allowed regions”

Two-neutrino oscillation

Atmospheric

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

n excess



$\Delta m^2_{LSND} \approx 1\ eV^2$

$\sin^2 2\theta \approx 0.003$

$\nu_e \rightarrow \nu_x$

Electron deficit

$\Delta m^2_{solar} \approx 10^{-5}\ eV^2$

$\sin^2 2\theta \approx 0.8$ or 0.008

Matter enhanced (MSW effect)

$\Delta m^2_{solar} \approx 10^{-10}\ eV^2$

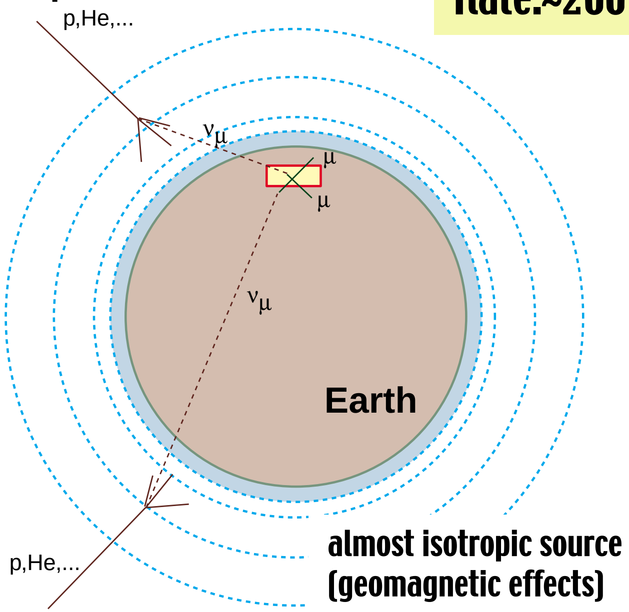
$\sin^2 2\theta \approx 0.8$

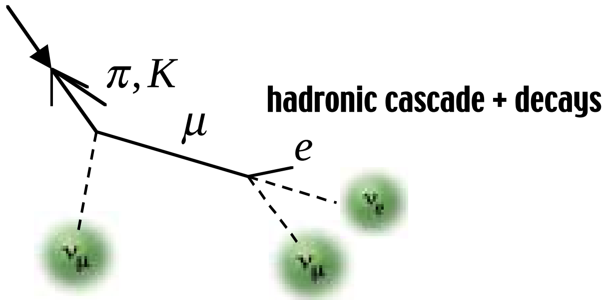
Vacuum oscillation

Atmospheric neutrinos

Earth is a splendid neutrino beam line!

Rate:≈200 events/kton/year





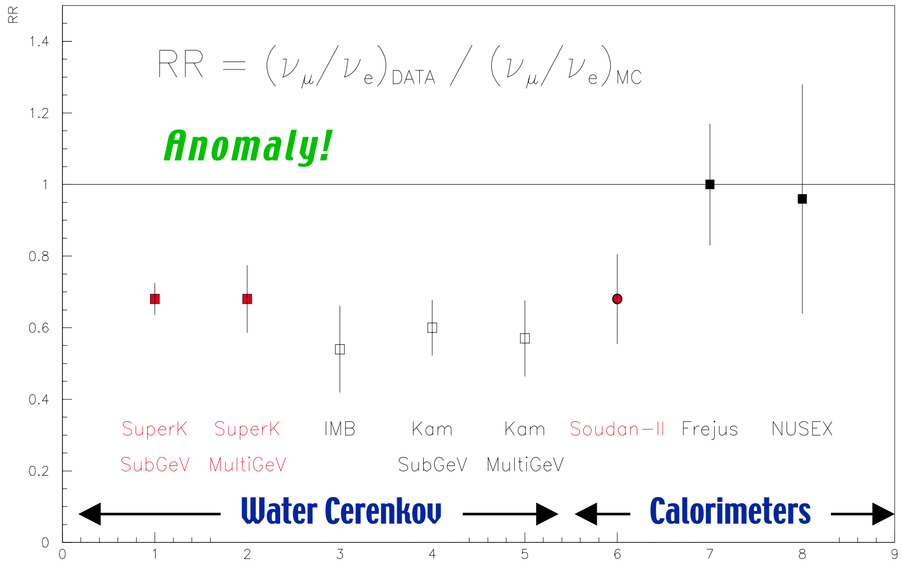
$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

Predicted ratio of muon to electron neutrinos

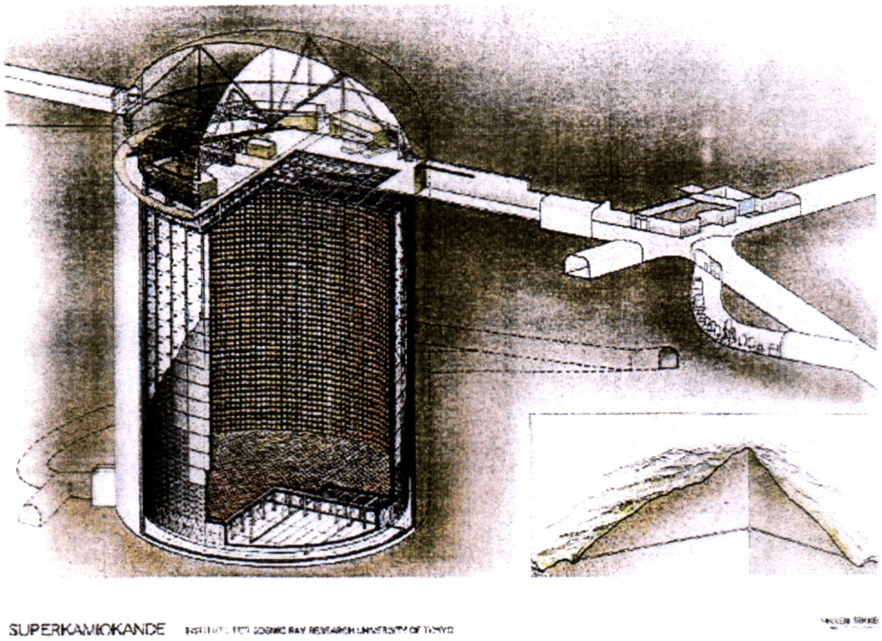
Use "double ratio":

$$RR \equiv \frac{(\mu/e)_{measured}}{(\mu/e)_{predicted}}$$

Experiment	Kt.year	RR
SuperK subGeV	**52.0**	**0.68–0.02–0.05**
SuperK multiGeV	**52.0**	**0.68–0.04–0.08**
IMB	7.7	0.54–0.05–0.11
Kam subGeV	6.1	0.60–0.06–0.05
Kam multiGeV	6.1	0.57–0.08–0.07
Soudan-II	**4.6**	**0.68–0.11–0.06**
NUSEX	0.4	0.96+0.32—0.28
Fr jus	2.0	1.00–0.15–0.08



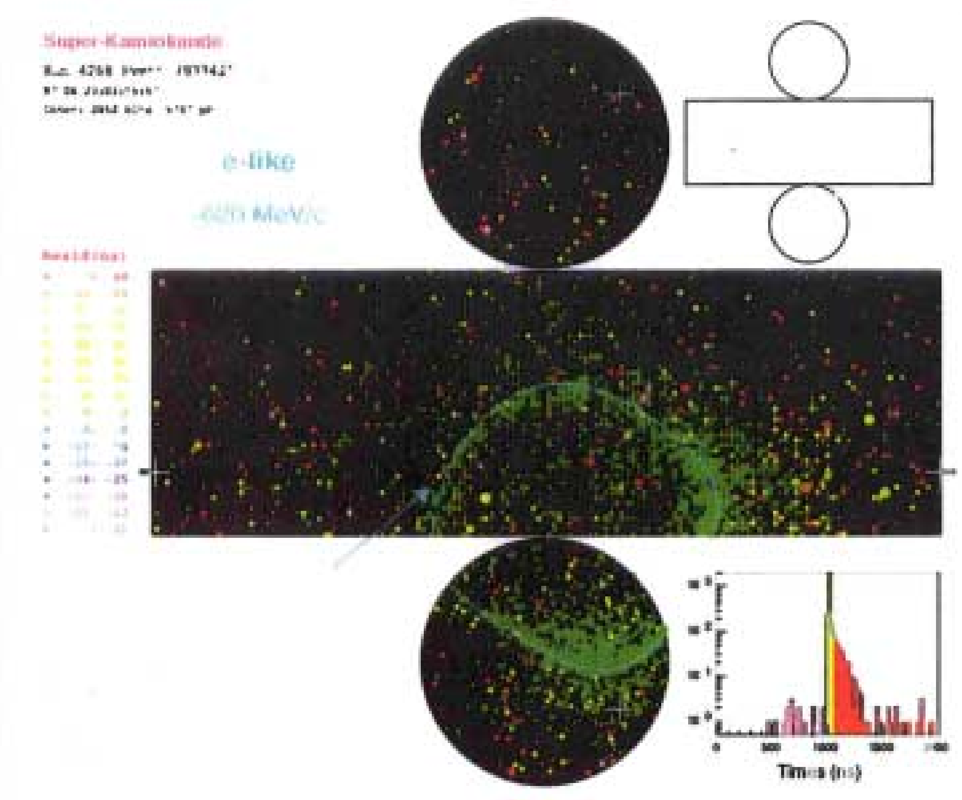
Super-Kamiokande

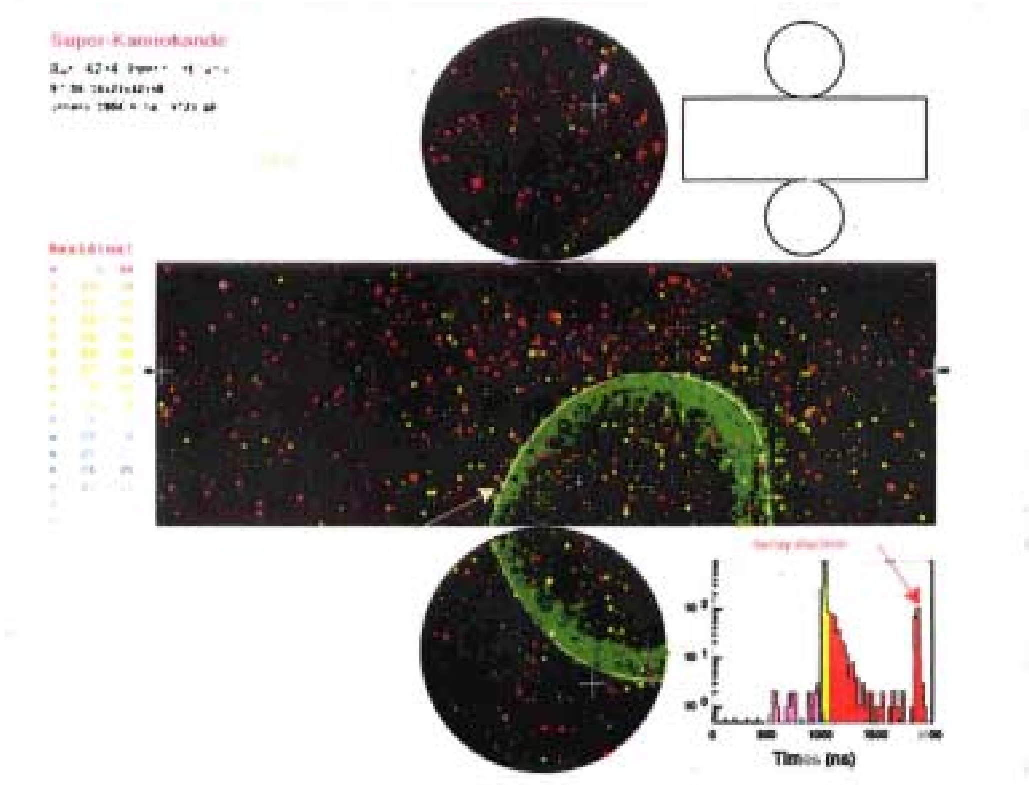


- Giant water Cherenkov detector
  - Total mass: 50,000 tons
  - Fiducial mass: 22,500 tons
  - Location: 1,000 m underground
  - Inner detector: 11,146 PMTs (50-cmϕ)
  - Outer detector: 1,885 PMTs (20-cmϕ)
- Operation since April 1996

K. Nakamura, NUFACT00, Monterey (USA), May 2000

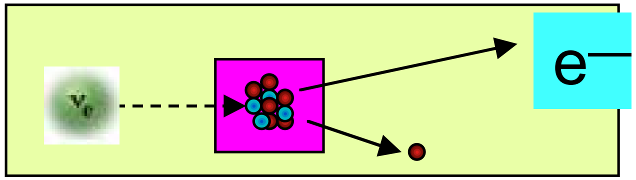
Electron and muon events in Superkamiokande

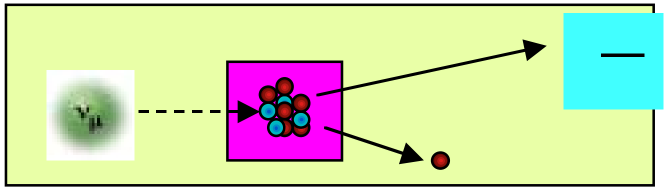




Electron-like event

Muon-like event





Note: at high energy, the direction & energy of outgoing e/ is ¯ that o f incoming neutrino

Sub-GeV, Multi-GeV Event Summary

Sub-GeV event Summary

Evis < 1.33GeV
P_e > 100MeV/c
P_μ > 200MeV/c

	DATA	MC(Honda)	MC(Bartol)
1R	4363	5219.2	5095.0
e-like	2185	2081.8	2049.1
μ-like	2178	3137.4	3045.9
2R	1144	1359.1	1337.2
≥3R	493	652.4	651.0
TOTAL	6000	7230.7	7083.2

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.661 \pm {}^{0.020}_{0.020}\,(\text{stat.}) \pm 0.052\,(\text{sys.})\ \text{(Honda)}$$

$$= 0.671 \pm {}^{0.021}_{0.020}\,(\text{stat.}) \pm 0.053\,(\text{sys.})\ \text{(Bartol)}$$

Multi-GeV event Summary

(1) FC (Evis > 1.33GeV)

	DATA	MC(Honda)	MC(Bartol)
1R	913	1121.3	1139.3
e-like	492	481.3	499.2
μ-like	421	640.0	640.1
2R	368	490.8	502.4
≥3R	659	783.0	817.5
TOTAL	1940	2395.1	2459.2

(2) PC

	DATA	MC(Honda)	MC(Bartol)
TOTAL	563	818.9	864.2

*All events are assumed to be μ-like.
*Fraction of CC ν_μ, $\bar{\nu}_\mu$ events in the PC sample is estimated to be (97-98)%.

$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}}$

FC + PC

$$= 0.660 \pm {}^{0.038}_{0.035}\,(\text{stat.}) \pm 0.078\,(\text{sys.})\ \text{(Honda)}$$

$$= 0.664 \pm {}^{0.038}_{0.036}\,(\text{stat.}) \pm 0.079\,(\text{sys.})\ \text{(Bartol)}$$

FC only

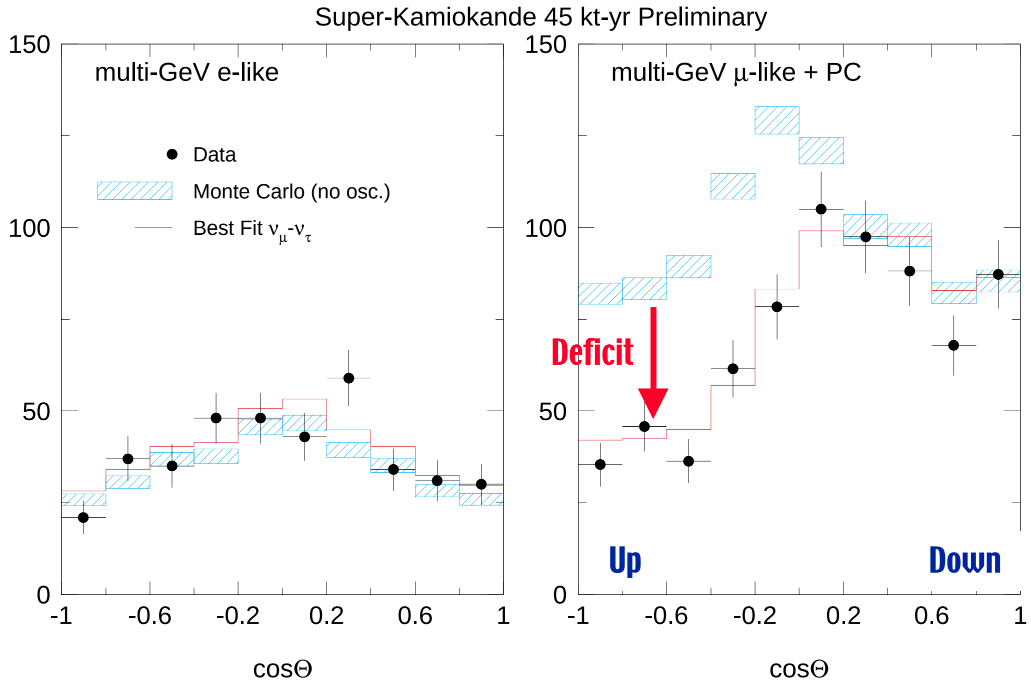
$$= 0.643 \pm {}^{0.044}_{0.042}\,(\text{stat.}) \pm 0.094\,(\text{sys.})\ \text{(Honda)}$$

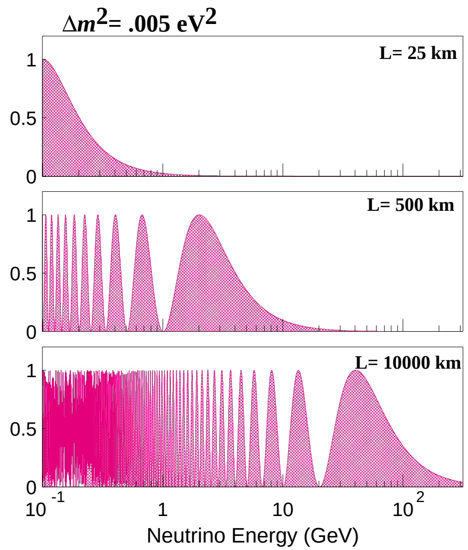
$$= 0.667 \pm {}^{0.046}_{0.043}\,(\text{stat.}) \pm 0.098\,(\text{sys.})\ \text{(Bartol)}$$

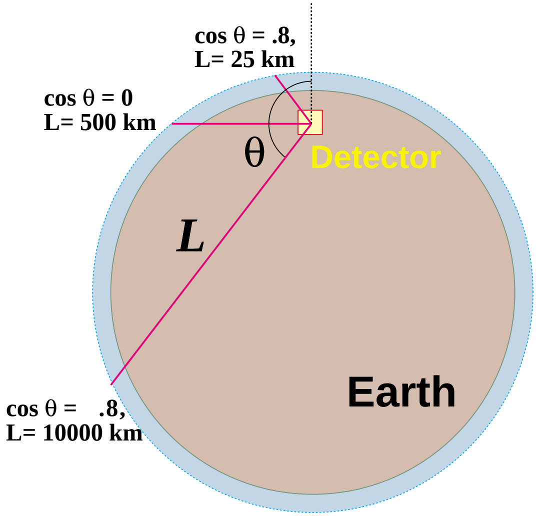
K. Nakamura, NUFACT00, Monterey (USA), May 2000

Zenith angle distribution

By looking in different zenith angle directions, one can select the neutrino "baseline" L…







$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

(Δm^2 in eV^2, L in km, E in GeV)

$\Rightarrow \nu_\mu \to \nu_\tau$ oscillations?

- ***ν_μ deficit increases with L***
- ***no apparent effect with ν_e***

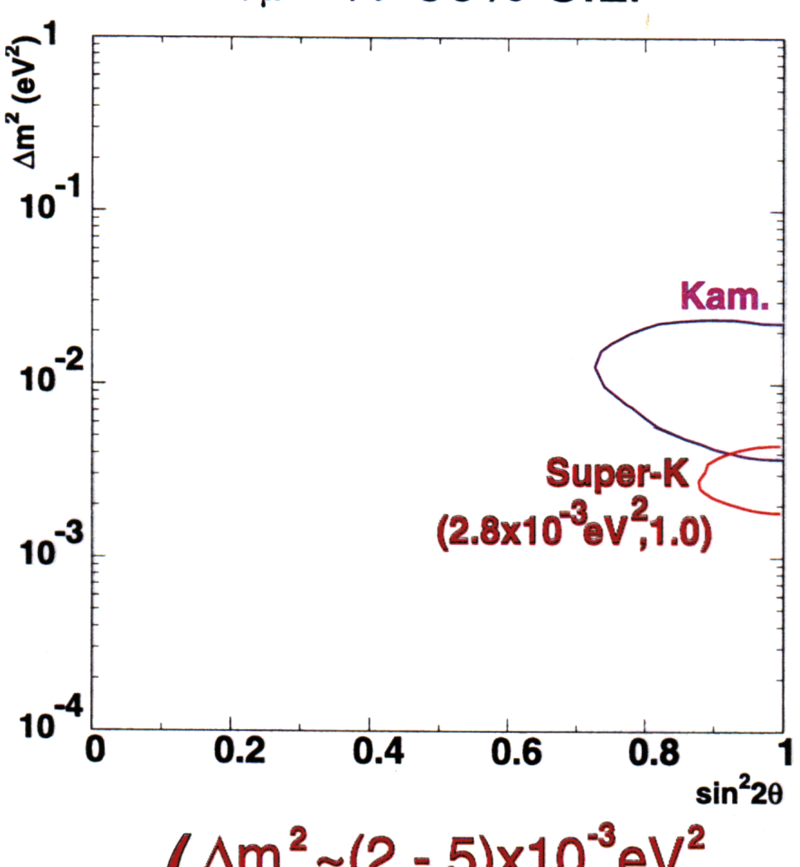
$$U_{\mu 3}^2 = U_{\tau 3}^2 \approx \frac{1}{2}$$

Maximal mixing

Allowed region for
FC + PC + up-going μ

Allowed region
(FC, PC, up-going μ)

$\nu_\mu \rightarrow \nu_\tau$ 90% C.L.

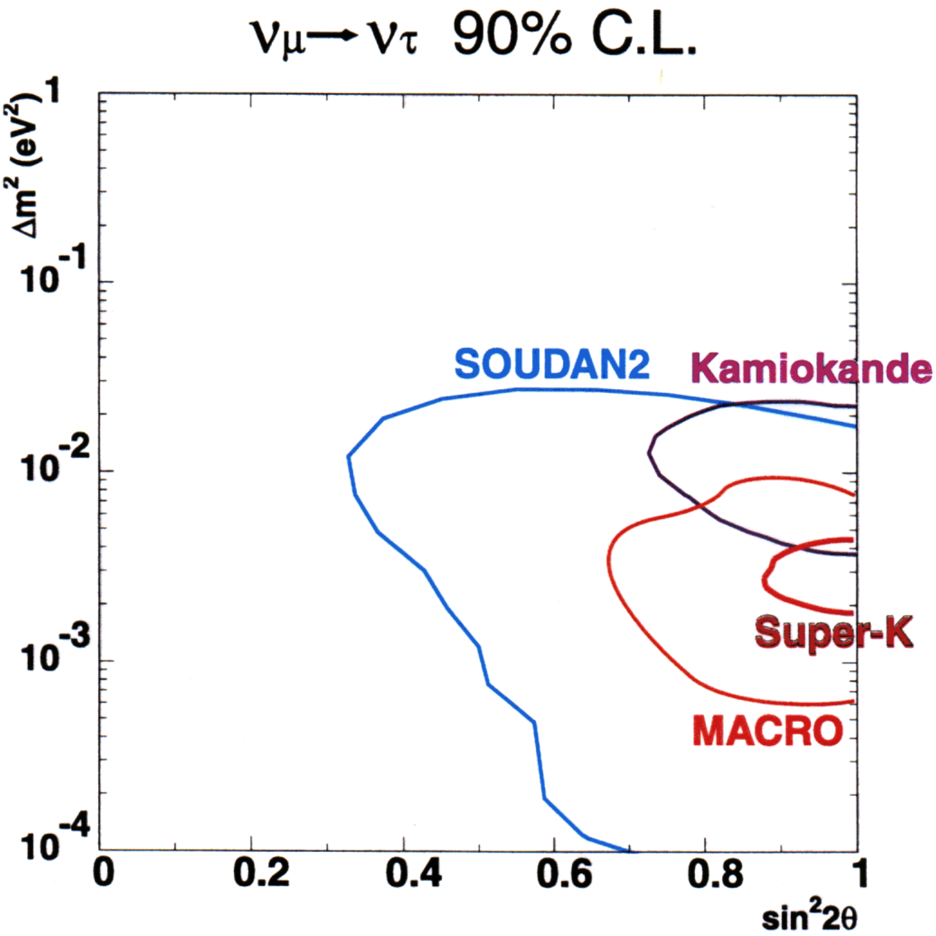


$\Delta m^2 \sim (2 - 5) \times 10^{-3} eV^2$,
$\sin^2 2\theta > 0.88$
(SK 90%C.L. preliminary)

K. Nakamura, NUFACT00, Monterey (USA), May 2000

Comparison of allowed regions

Allowed regions



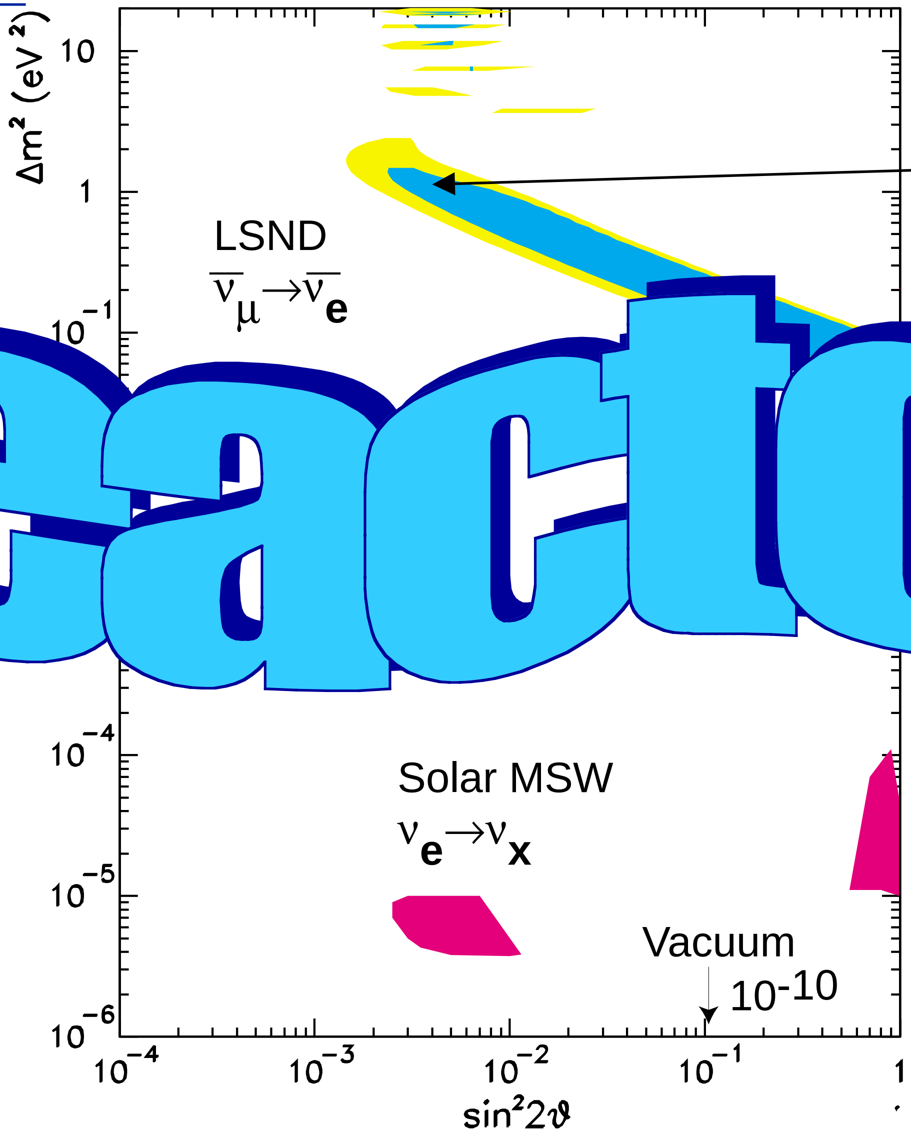
K. Nakamura, NUFACT00, Monterey (USA), May 2000

Oscillation map - “allowed regions”

Two-neutrino oscillation

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

Reactors



$\Delta m^2_{LSND} \approx 1\ eV^2$

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$\nu_e \rightarrow \nu_x$

Electron deficit

$\Delta m^2_{solar} \approx 10^{-5}\ eV^2$

$\sin^2 2\theta \approx 0.8$ or 0.008

Matter enhanced (MSW effect)

$\Delta m^2_{solar} \approx 10^{-10}\ eV^2$

$\sin^2 2\theta \approx 0.8$

Vacuum oscillation

$$P_{x \to y} = \sin^2 2\theta \ \sin^2 \frac{1.27 \ \Delta m^2 \ L}{E_\nu}$$

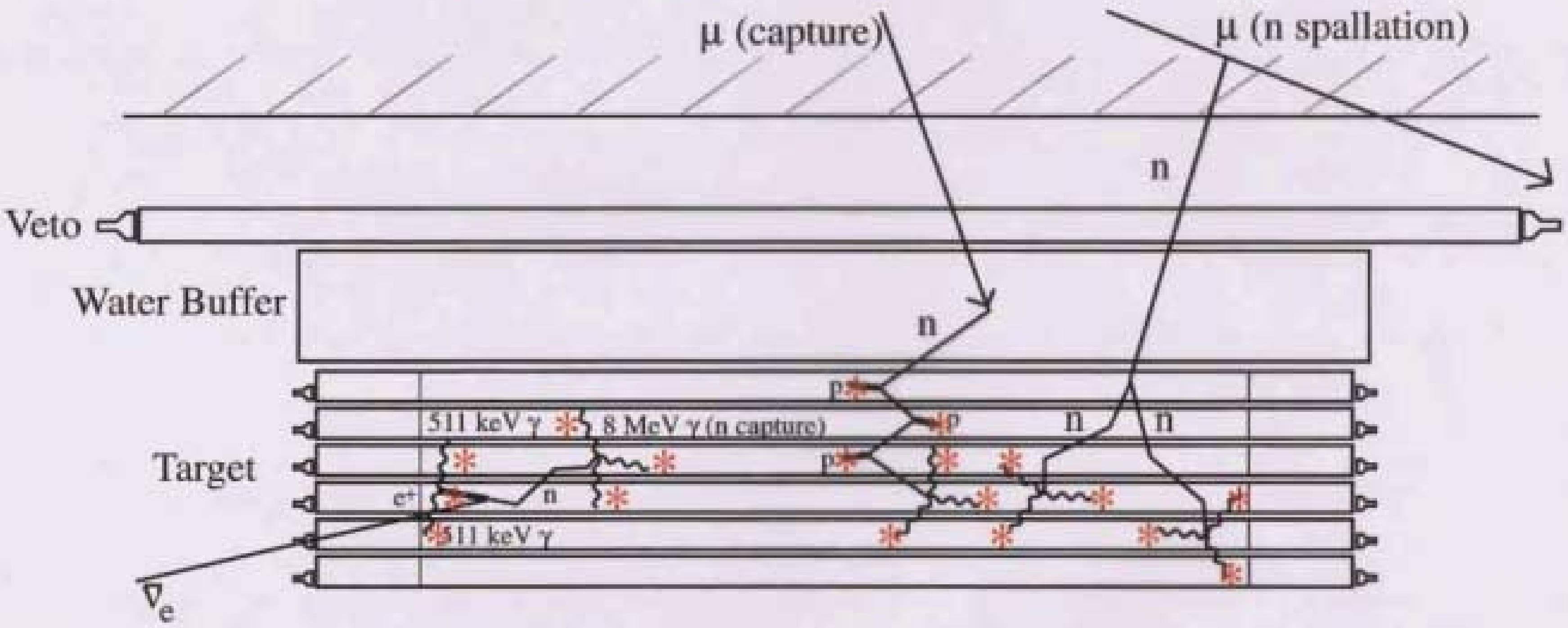
Complementary Properties of Reactor and Accelerator Oscillation Experiments

E_ν = few MeV	**E_ν = few GeV**
- *Probe small Δm^2*	- *Good mass sensitivity requires very large L*
- *Disappearance only (fair $\sin^2 2\theta$ sensitivity)*	- *Appearence possible (produce μ and τ)*
- *4 π source (detector mass grows with L^2)*	- *(More) collimated beam*

G. Gratta, Neutrino2000

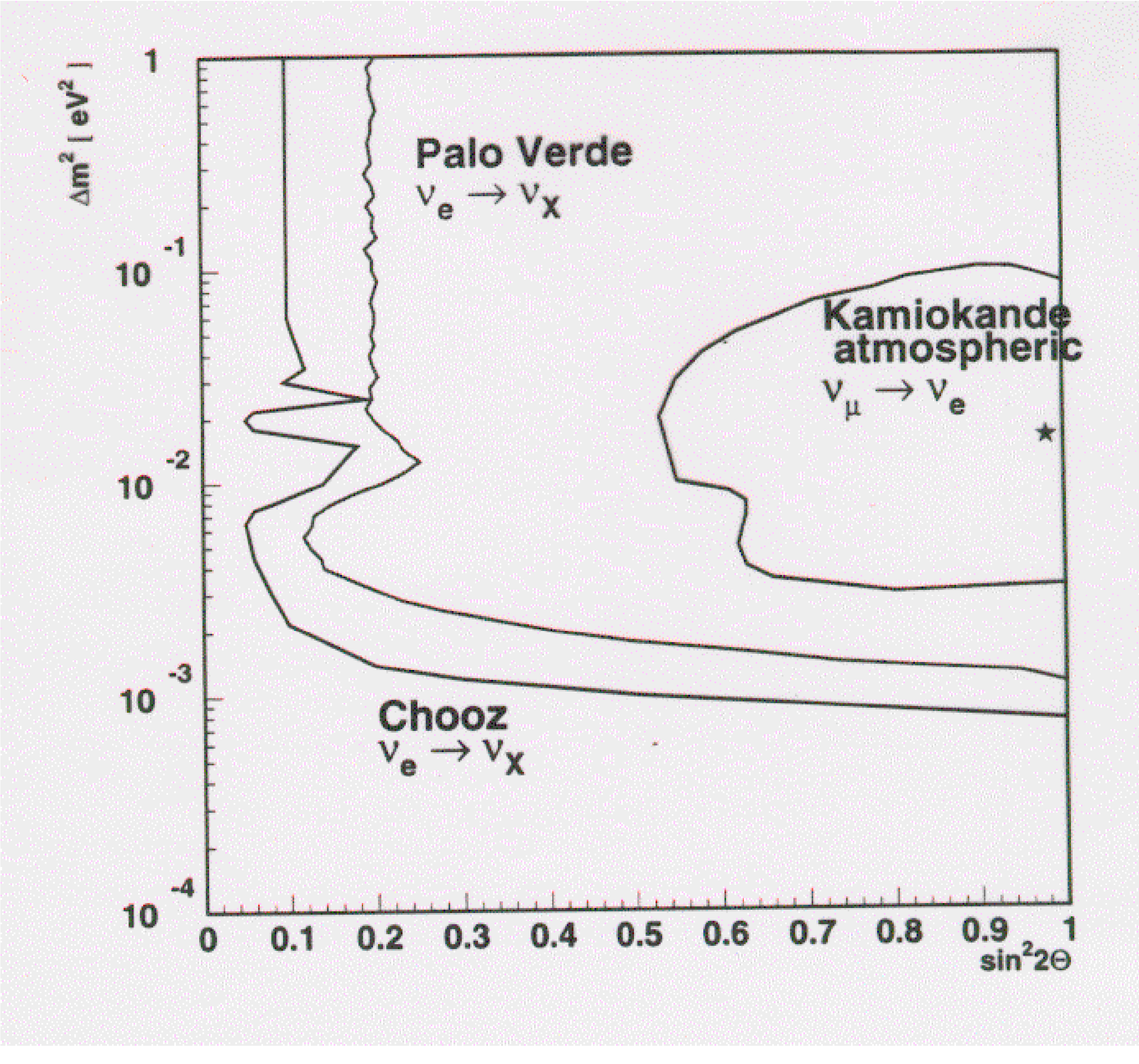
Signal consists of 2 triples, separated by n-capture time

Gd-loading: - fast capture ($\approx$30 μs instead of $\approx$200 μs on p)
- 8 MeV (total) high mult. γ cascade at capture



$$E_\nu \simeq E_{e^+} + (M_n + M_p + m_{e^+}) + m_{e^+}$$

G. Gratta, Neutrino2000



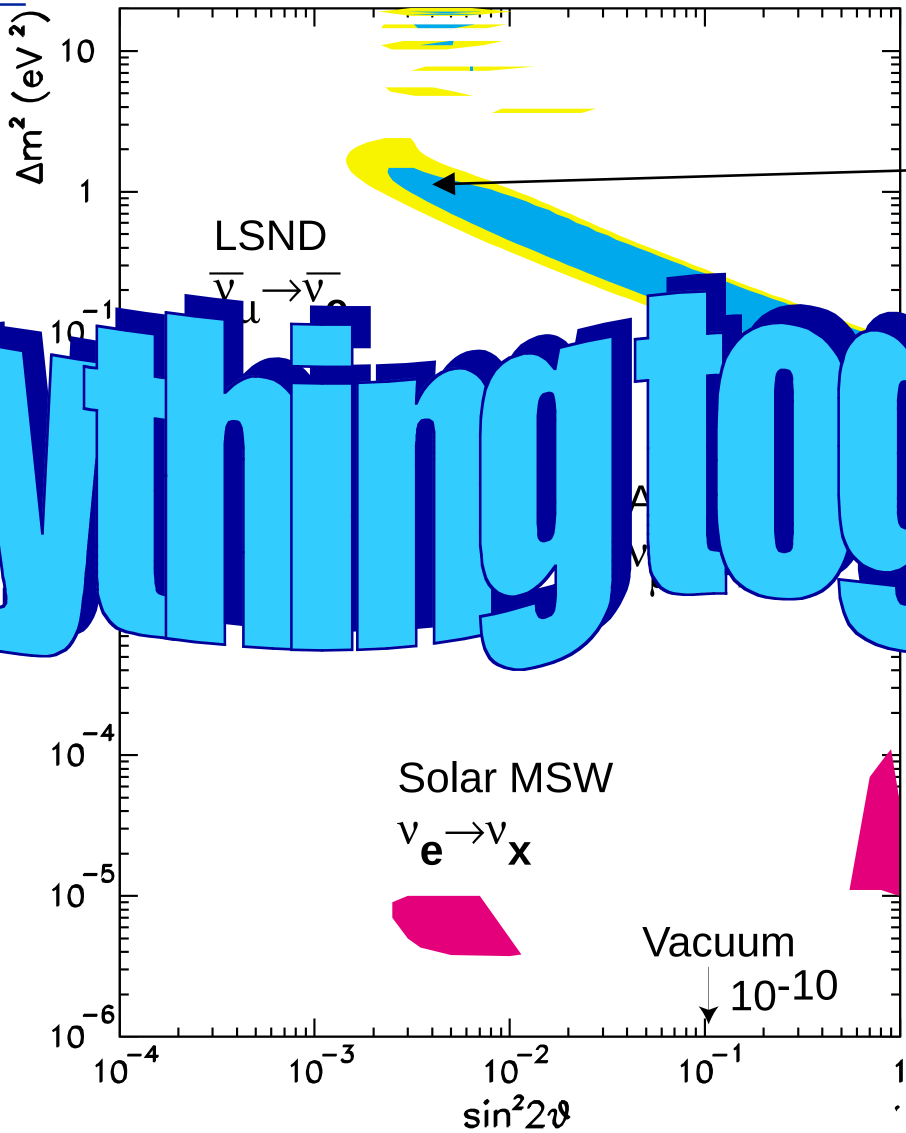
G. Gratta, Neutrino2000

Oscillation map - "allowed regions"

Two-neutrino oscillation

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

Electron excess



Everything together

$\Delta m^2_{LSND} \approx 1\ eV^2$

$\sin^2 2\theta \approx 0.003$

muon deficit

$\nu_e \rightarrow \nu_x$

Electron deficit

$\Delta m^2_{solar} \approx 10^{-5}\ eV^2$

$\sin^2 2\theta \approx 0.8$ or 0.008

Matter enhanced (MSW effect)

$\Delta m^2_{solar} \approx 10^{-10}\ eV^2$

$\sin^2 2\theta \approx 0.8$

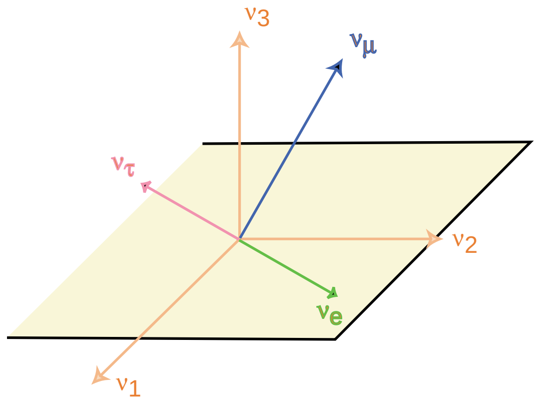
Vacuum oscillation

Three flavor mixing

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Weak eigenstates

Mass eigenstates



$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = P_{CP}(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) \pm P_{\not{C}\not{P}}(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta)$$

CP-conserving

$$P_{CP} = \delta_{\alpha\beta} - 4\sum_{j>k} \mathrm{Re}\, J_{\alpha\beta jk} \sin^2 \Delta_{jk}$$

CP-violating

$$P_{\not{C}\not{P}} = 4\sum_{j>k} \mathrm{Im}\, J_{\alpha\beta jk} \sin \Delta_{jk} \cos \Delta_{jk}$$

$$J_{\alpha\beta jk} = U_{\alpha k} U^*_{\beta k} U^*_{\alpha j} U_{\beta j}$$

Mixing strength

$$\Delta_{jk} = \frac{1.27\ \Delta m^2_{jk} L}{E}$$

Oscillatory pattern

Δm^2_{jk} in eV^2, L in km, E in GeV

In general, the oscillation pattern may be complicated and involve **a combination of transitions** to ν_e, ν_μ, ν_τ and by symmetry with quark sector **it is natural to expect CP violation** at some level.

Three family oscillations

➡ *Parameterization à la CKM:*

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

($s_{13}e^{-i\delta}$: U_{e3})

➡ *Current standard mass and mixing assignment:*

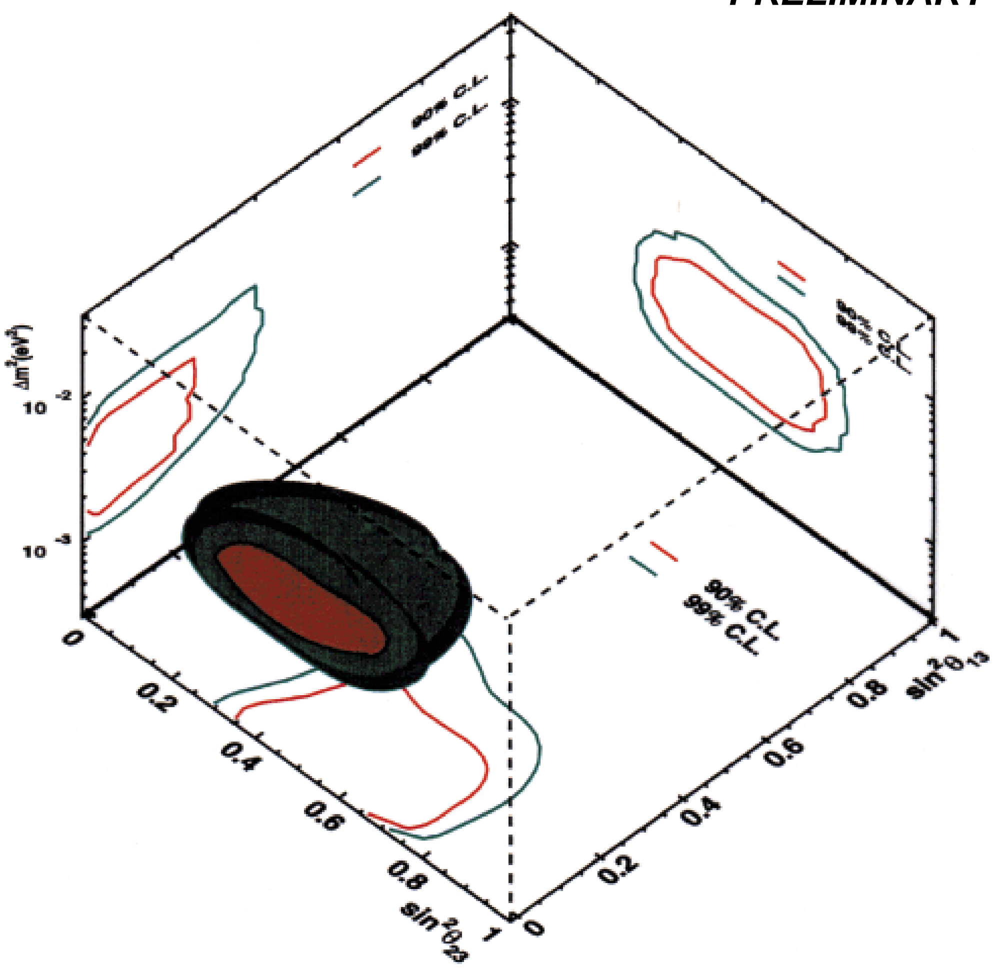
Atmospheric anomaly: $\nu_\mu \to \nu_\tau$ — $\Delta m^2_{32} \approx \Delta m^2_{31} \approx 3\text{x}10^{-3}$ eV^2, $\theta_{23} \approx 45°$

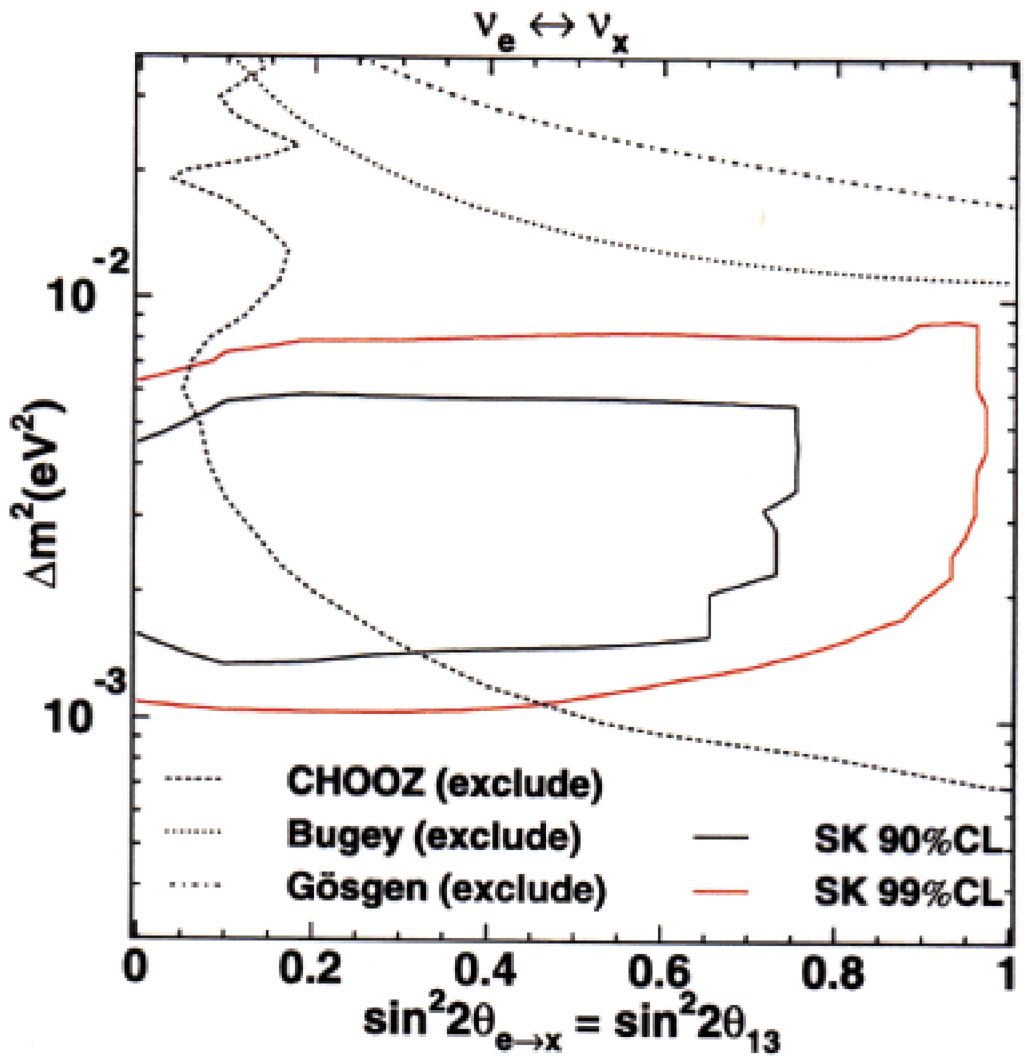
$\nu_\mu \to \nu_e$ $\quad \nu_e \to \nu_\tau$ — θ_{13} (small)

Solar deficit: $\nu_e \to \nu_{\mu/\tau}$ — Δm^2_{12}, θ_{12}, θ_{23}

$P(\nu_\alpha \to \nu_\beta) \overset{?}{\neq} P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ — $\delta \neq 0$?

3 flavor mixing analysis of atmospheric



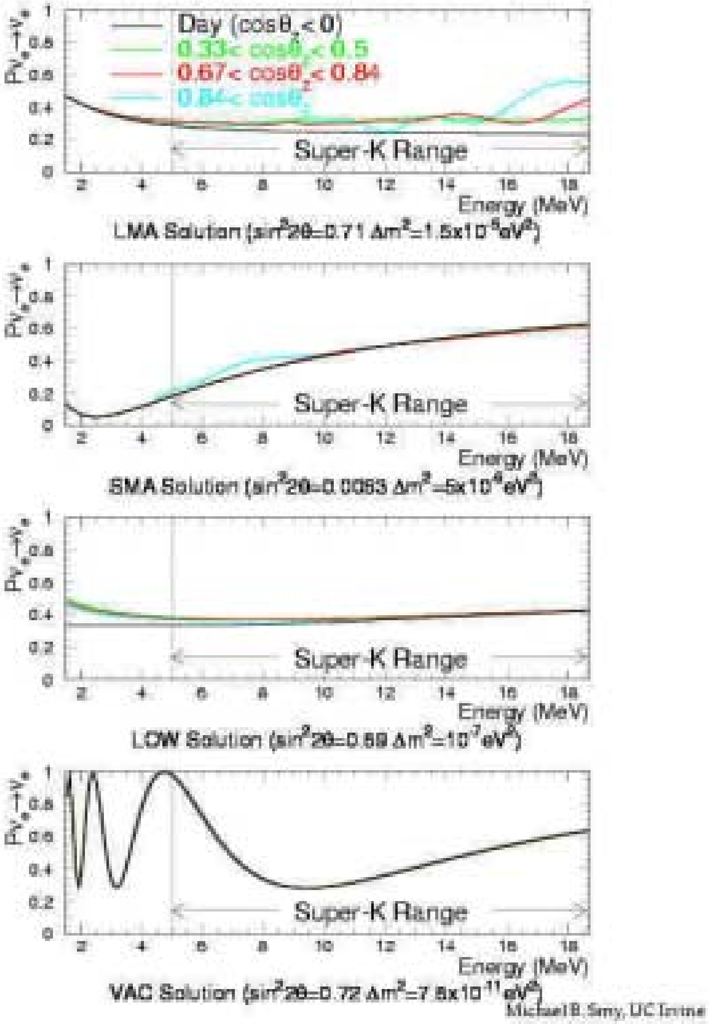


Atmospheric neutrinos analysis

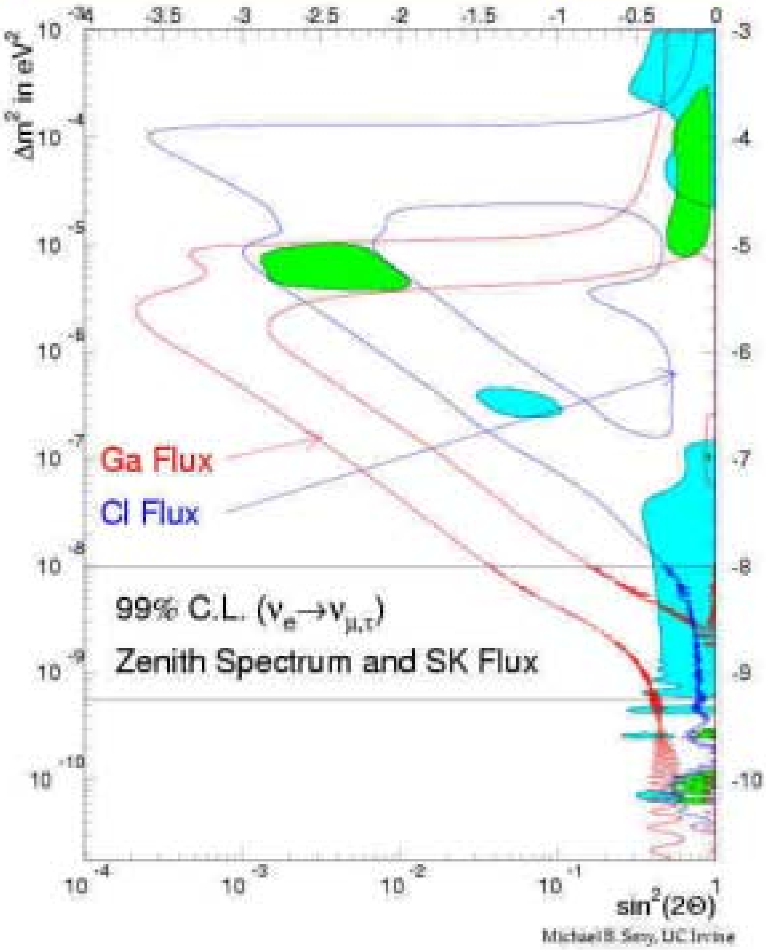
K. Nakamura, NUFACT00, Monterey (USA), May 2000

Solar neutrinos

Survival Probabilities



$$\nu_e \longleftrightarrow \nu_\mu$$



M.B. Smy, NOON2000, Tokyo (Japan), Dec 2000

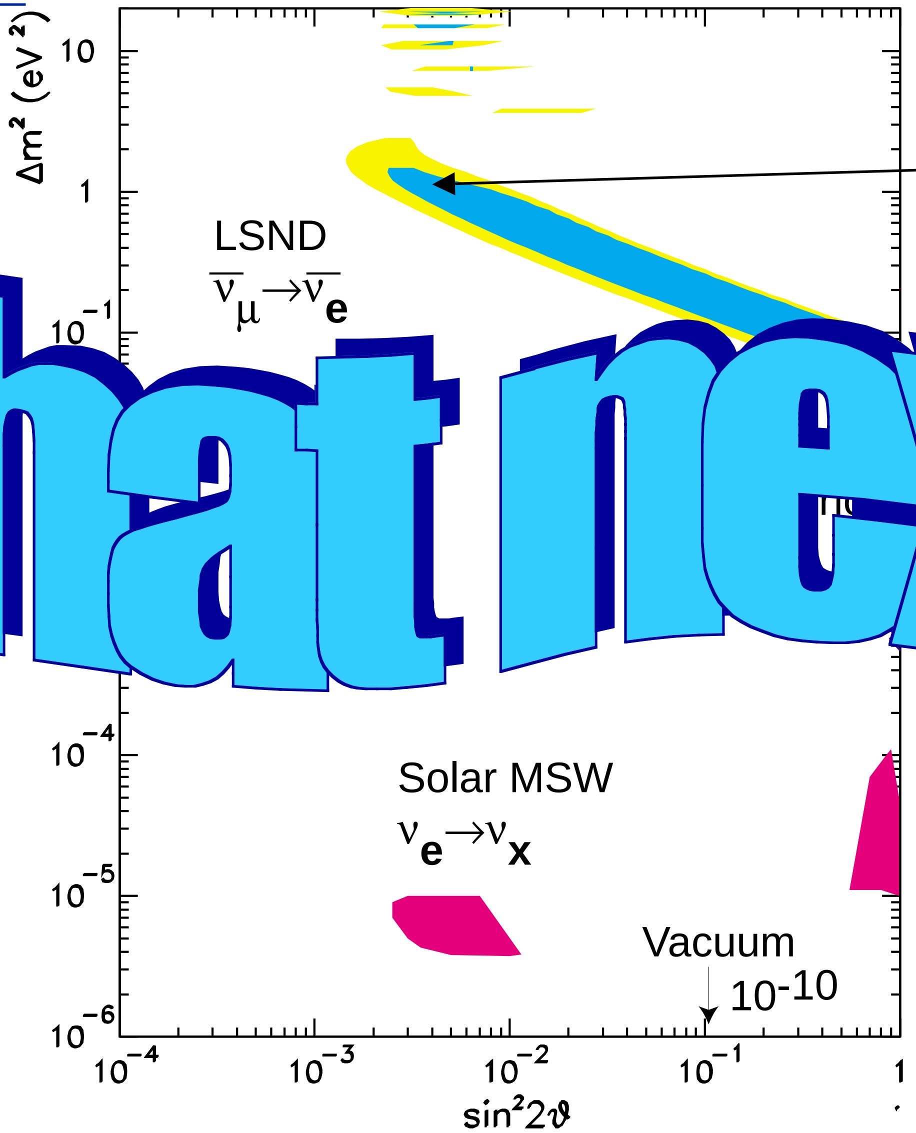
No smoking gun ?

Oscillation map - “allowed regions”

Two-neutrino oscillation

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

Electron excess



$\Delta m^2_{LSND} \approx 1\ eV^2$

$\sin^2 2\theta \approx 0.003$

10^{-3}

What next ?

$\nu_e \rightarrow \nu_x$

Electron deficit

$\Delta m^2_{solar} \approx 10^{-5}\ eV^2$

$\sin^2 2\theta \approx 0.8$ or 0.008

Matter enhanced (MSW effect)

$\Delta m^2_{solar} \approx 10^{-10}\ eV^2$

$\sin^2 2\theta \approx 0.8$

Vacuum oscillation

K2K (KEK-to-Kamioka)

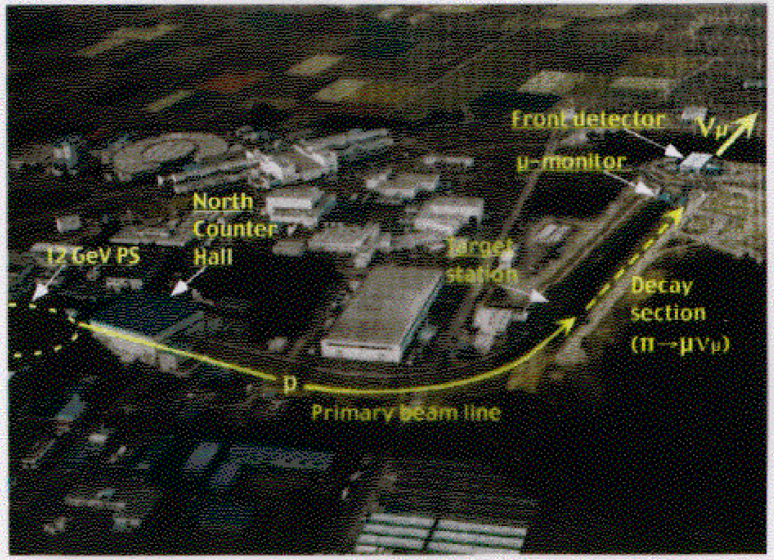
Super Kamiokande

Water Cherenkov detector

Total mass:	50 kton
Inner mass:	32 kton
Fiducial mass:	22.5 kton

KEK

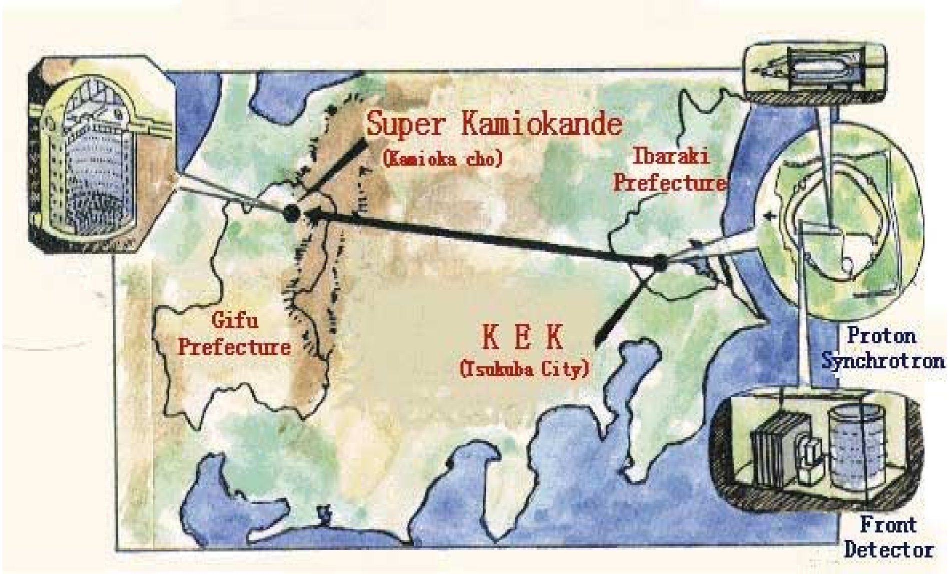
- Accelerator: 12 GeV proton synchrotron
  - Beam intensity: 6×10^{12} protons / pulse
  - Repetition: 1 pulse / 2.2 sec
  - Pulse width: 1.1 μs (9 bunches)
- Horn-focused wide-band beam
  - Average neutrino energy: 1.4 GeV → $\nu_\mu - \nu_\tau$ disappearence
- Near detector: 300 m from the target
- Far detector (Super-Kamiokande): 250 km from the target
- Goal: 10^{20} protons on target



Naka~ - 03

K2K experiment

- Experiment started in March 1999
  - ➜ Some initial problems with optics system now apparently solved
  - ➜ Beam intensity : 5.5 x 10^{12} ppp
  - ➜ Total integrated (Apr99-Mar 00): **16.64 x 10^{18} pots** (goal: 10^{20} pots)
- ***Beam measured with near detectors*** (FD)
  - ➜ 3 different detectors: 1kt H_2O, SCIFI tracker+water, MUC (Fe μ ranger)
  - ➜ Event rate & energy spectrum under study
- ***Extrapolation at far detector*** (SK)

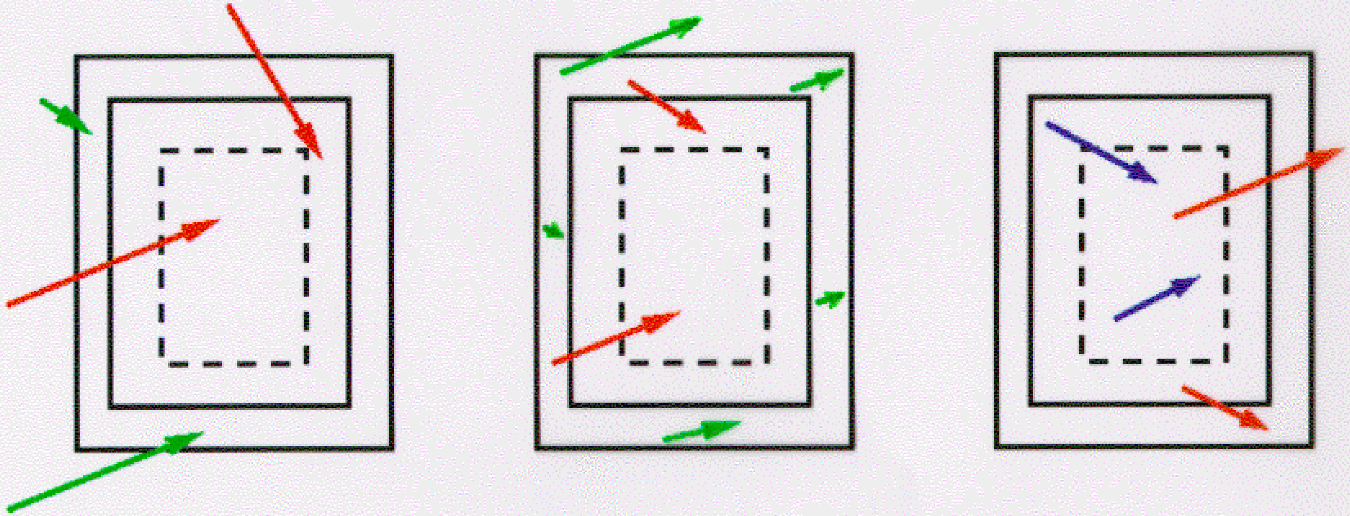


L = 250 km
$E_\nu \approx 1$ GeV

Expected@SK: 29.2±3.5
Events seen: 17 events

⇒Disfavors no oscillations at 2σ level!

SK event category



Vertex in rock — Vertex in OD — Vertex in ID

- FC (Fully Contained; Light in ID only)
  - Vertex inside the 22.5 kton fiducial volume
  - Vertex outside the fiducial volume
- OD contained (Light in OD only)
- Crossing (Light in both ID and OD)

K. Nakamura, Neutrino2000

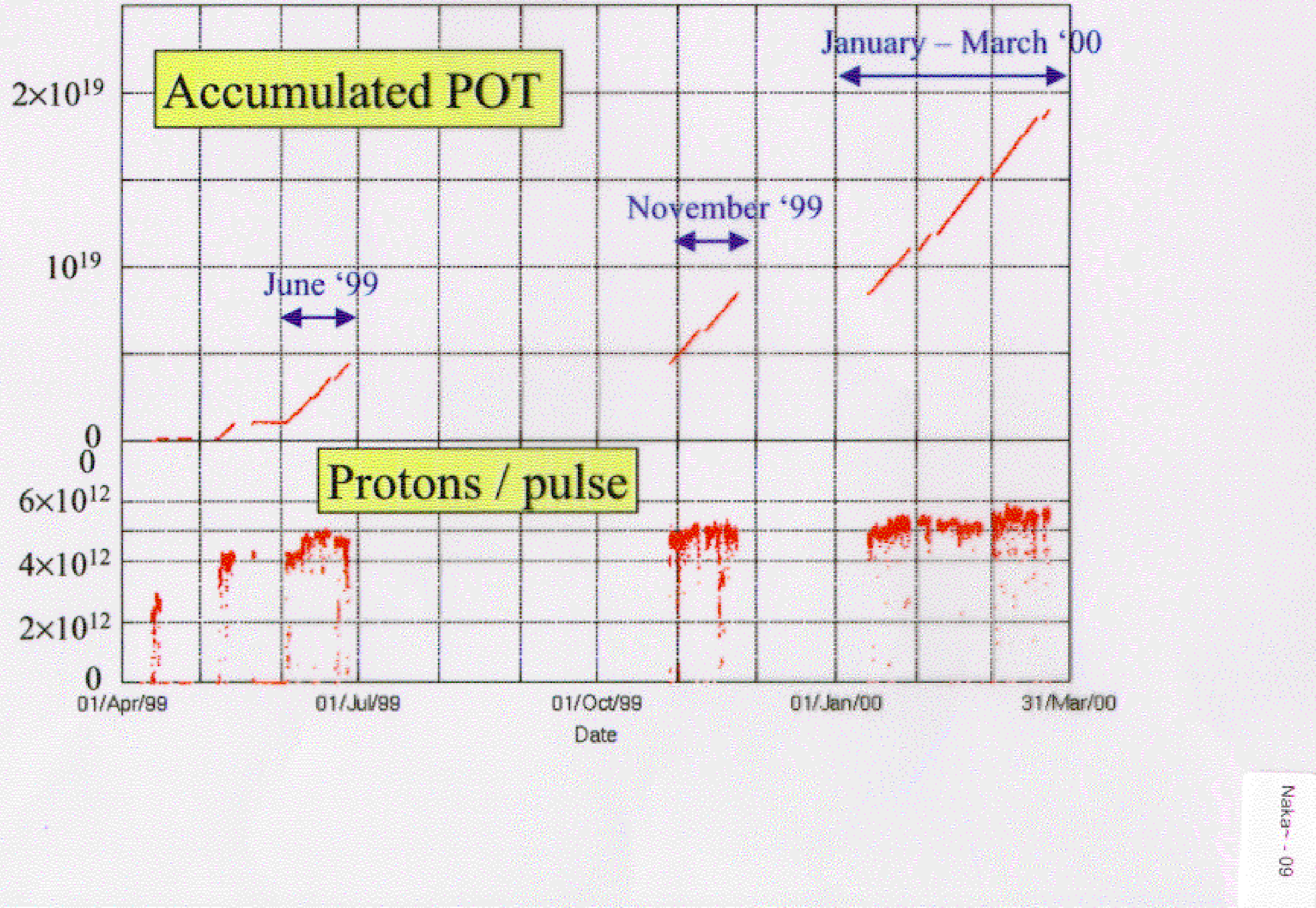
SK observed vs. expected

	Obs.	Null Osc.	Expected $\Delta m^2(\times 10^{-3} eV^2)$ $\sin^2 2\theta = 1$: 3	5	7
FC 22.5kt	17	$29.2^{+3.5}_{-3.3}$	$19.3^{+2.5}_{-2.4}$	$12.9^{+1.6}_{-1.6}$	$10.8^{+1.4}_{-1.3}$
1-ring	10	17.6±2.5	10.4±1.7	6.8±1.1	6.2±1.0
μ-like	9	15.8±2.6	9.0±1.5	5.4±0.9	4.9±0.8
e-like	1	1.7±0.3	1.5±0.3	1.4±0.3	1.3±0.3
multi ring	7	11.6±2.0	8.8±1.6	6.1±1.1	4.6±0.8
FC Out of FV	9	12.4±2.5	8.1±1.7	5.5±1.1	4.8±1.0
OD contained	8	21.8±8.3	14.5	9.5	7.7
Crossing	10	10.4±3.8	7.9	5.2	3.6

Naka~ - 19

K. Nakamura, Neutrino2000

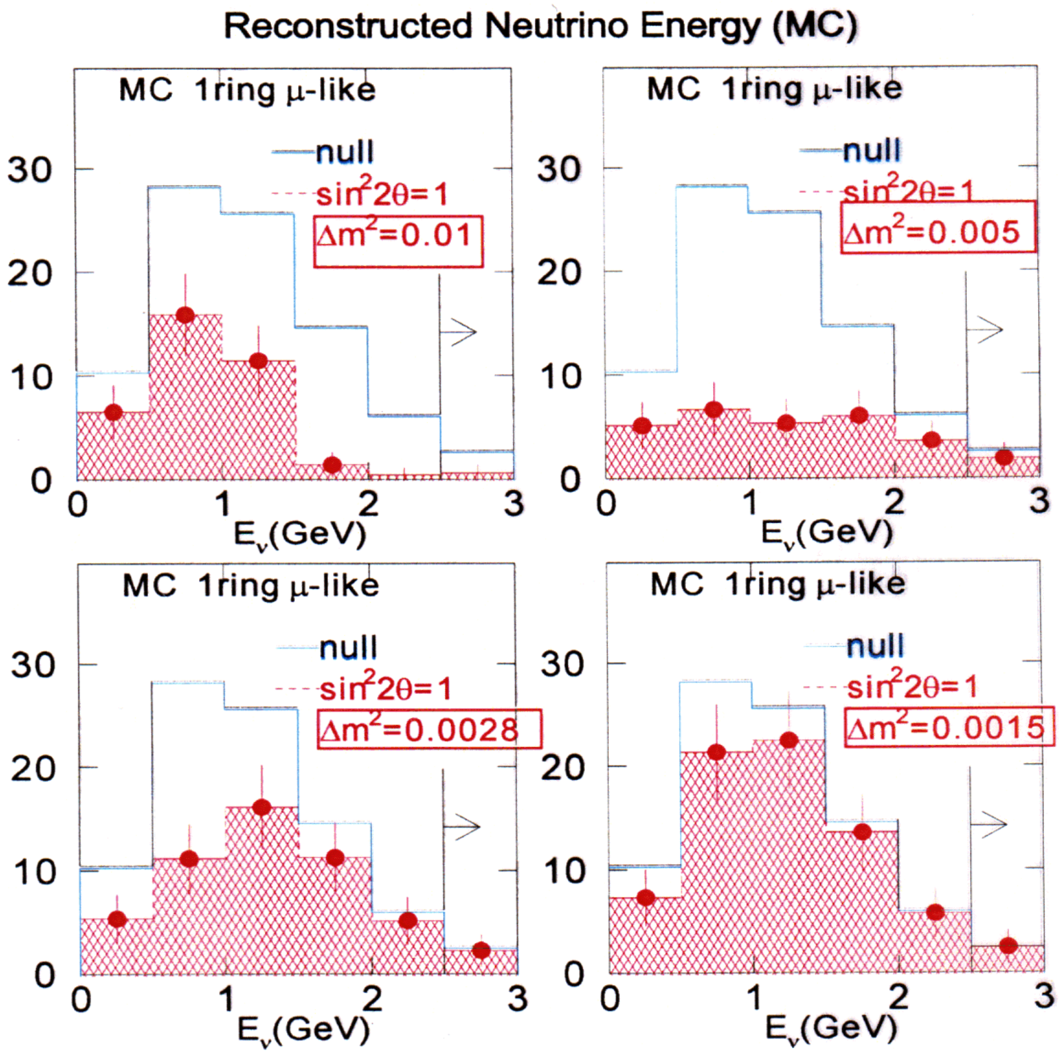
Protons delivered to the target



K. Nakamura, Neutrino2000

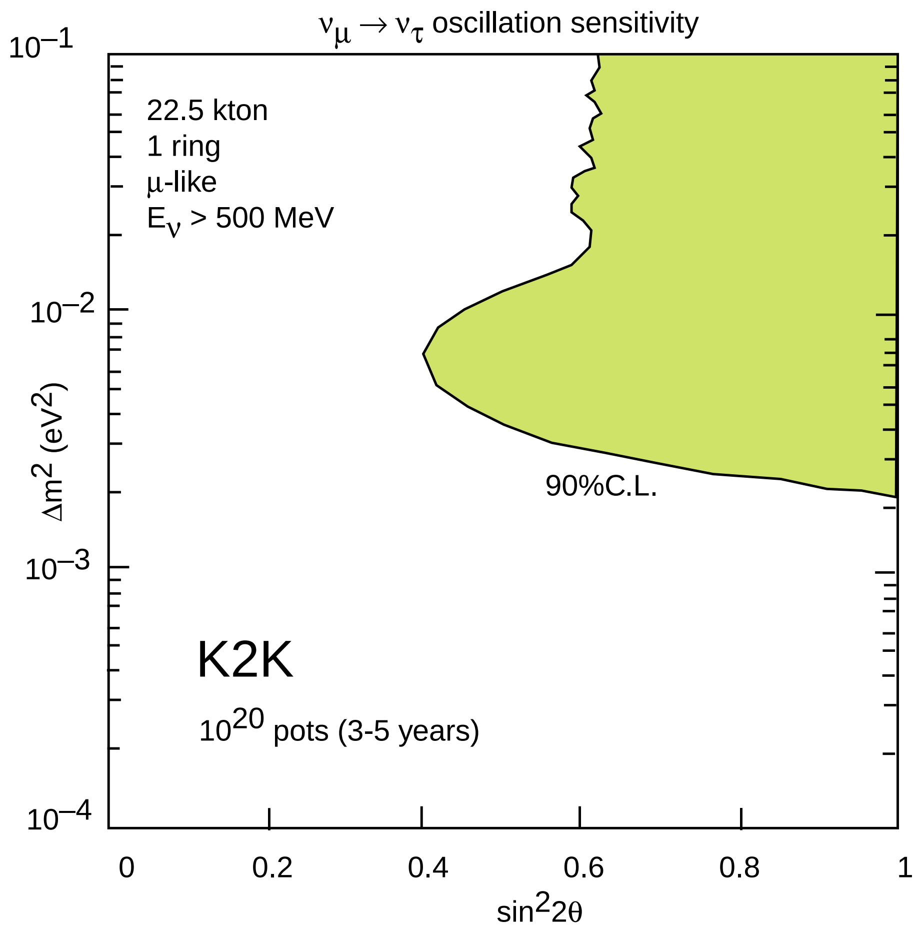
Expected SK events at 10^{20} POT

172 interactions in 22.5ktons
88 μ candidates



K. Nakamura, NUFACT00, Monterey (USA), May 2000

K2K sensitivity



1. Will provide first confirmation of muon disappearance with artificial beam!

✓ $\nu_\mu \rightarrow \nu_x$

2. Measurement of Δm^2 & $\sin^2 2\theta$

Limited by statistics

3. No unambiguous flavor oscillation signature?

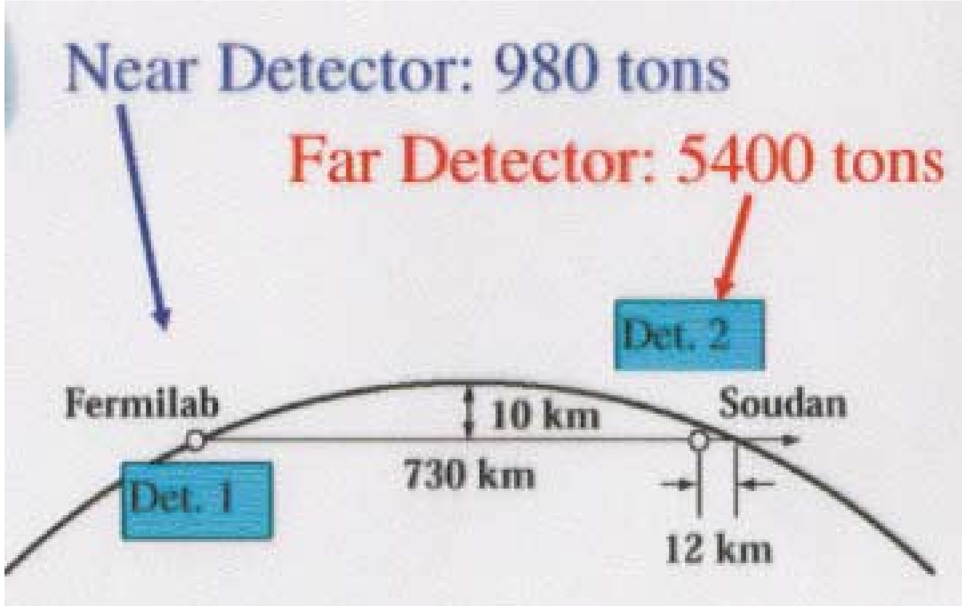
$\nu_\mu \xrightarrow{?} \nu_\tau \rightarrow \tau + X$ (crossed out)

Neutrino energy is below production threshold

4. Subdominant $\nu_\mu \rightarrow \nu_e$ sensitivity?

Poor (statistics, „ ^{0} contamination)

NUMI-MINOS program (U.S.A.)



1. Will provide second confirmation of muon disappearance with artificial beam (near-far comparison)!

2. Precise measurement (±10%) of Δm^2 & $\sin^2 2\theta$

3. No unambiguous flavor oscillation signature

Limited by detector granularity

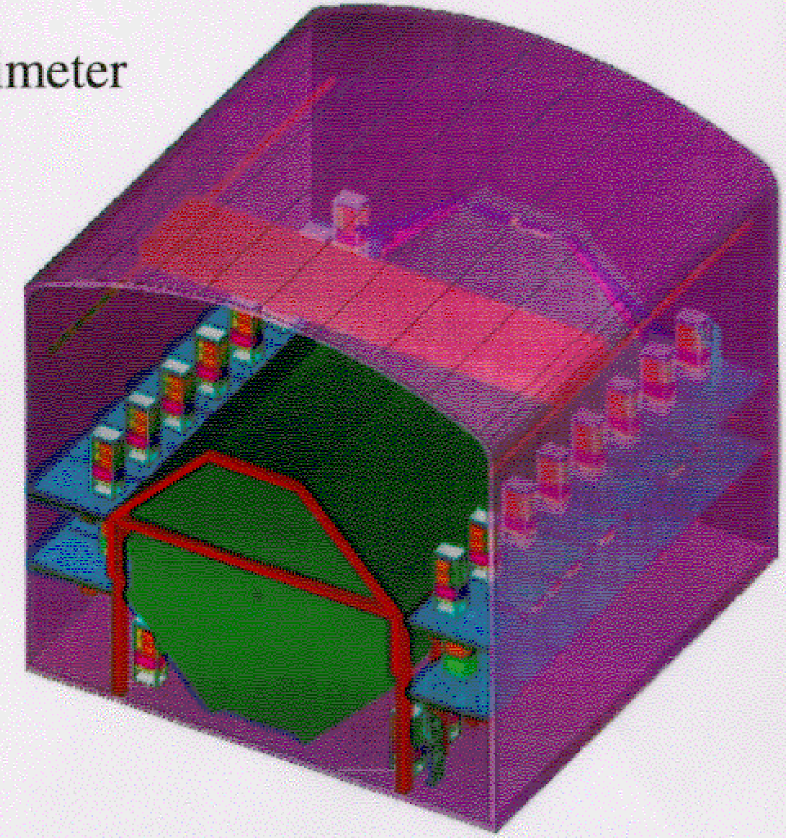
4. Subdominant $\nu_\mu \rightarrow \nu_e$ *sensitivity?*

Poor (π^0 contamination)

Neutrino 2000
June 17, 2000
Page 9

MINOS Far Detector

- 8m Octagonal Tracking Calorimeter
- 486 layers of 2.54cm Fe
- 2 sections, each 15m long
- 4.1cm wide solid scintillator strips with WLS fiber readout
- 25,800 m^2 active detector planes
- Magnet coil provides $\langle B \rangle \approx 1.3T$
- 5.4kt total mass



Half of the MINOS Far Detector

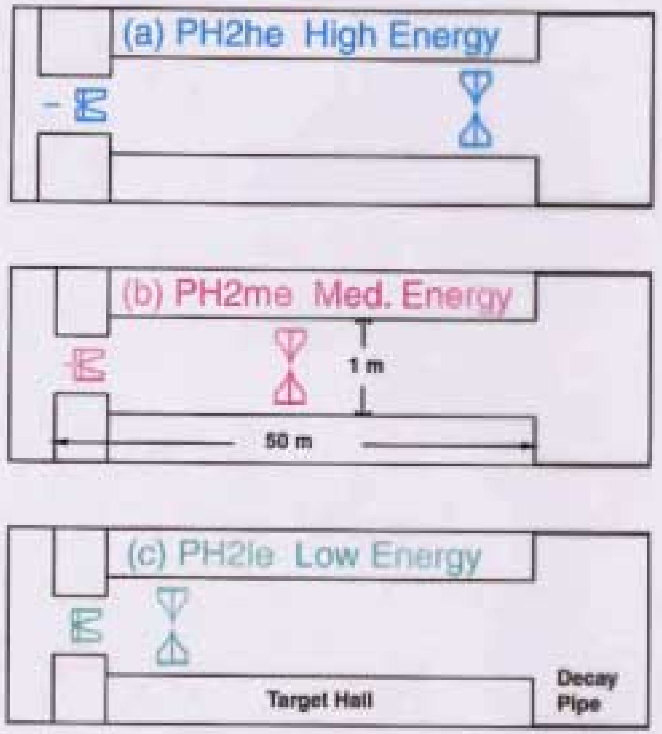
S. Wojcicki, Neutrino2000

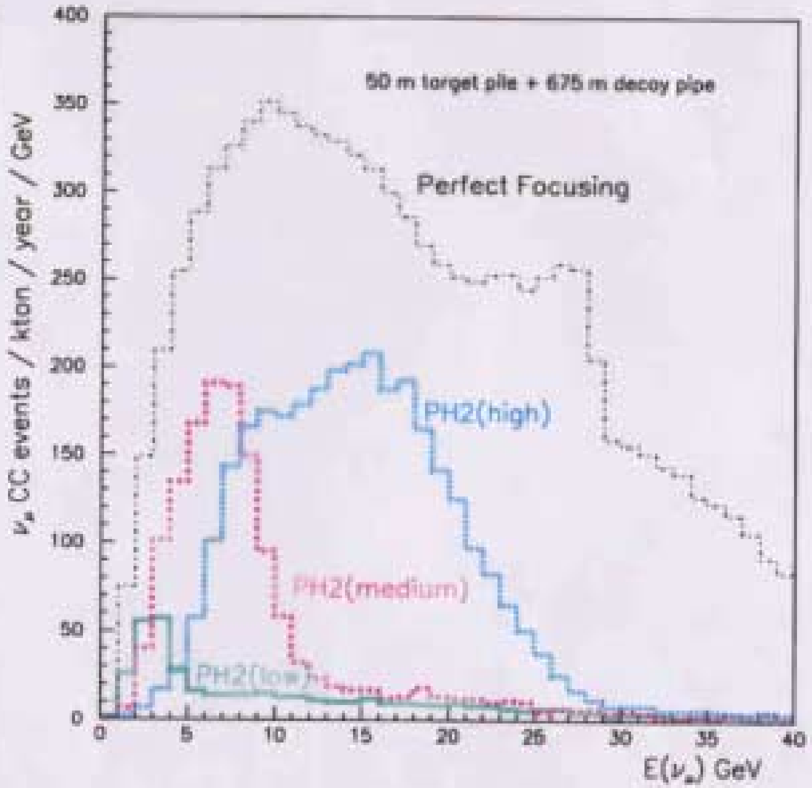
NUMI

MINOS

Tuning Neutrino Spectra by Horn/Target Reconfiguration

Neutrino 2000
June 17, 2000
Page 8





Wojcicki - 1

S. Wojcicki, Neutrino2000

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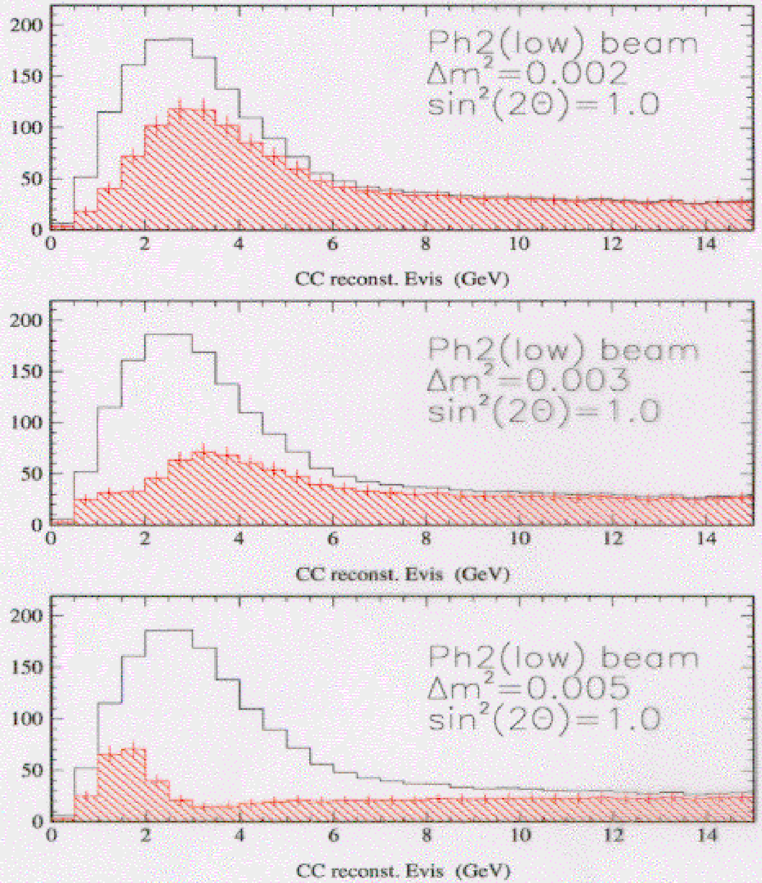
Neutrino 2000
June 17, 2000
Page 16

MINOS Energy Spectra



10 kt-yr Exposure

Solid lines - energy spectrum without oscillations

Dashed histogram - spectrum in presence of oscillations

Wojcicki - 17

S. Wojcicki, Neutrino2000

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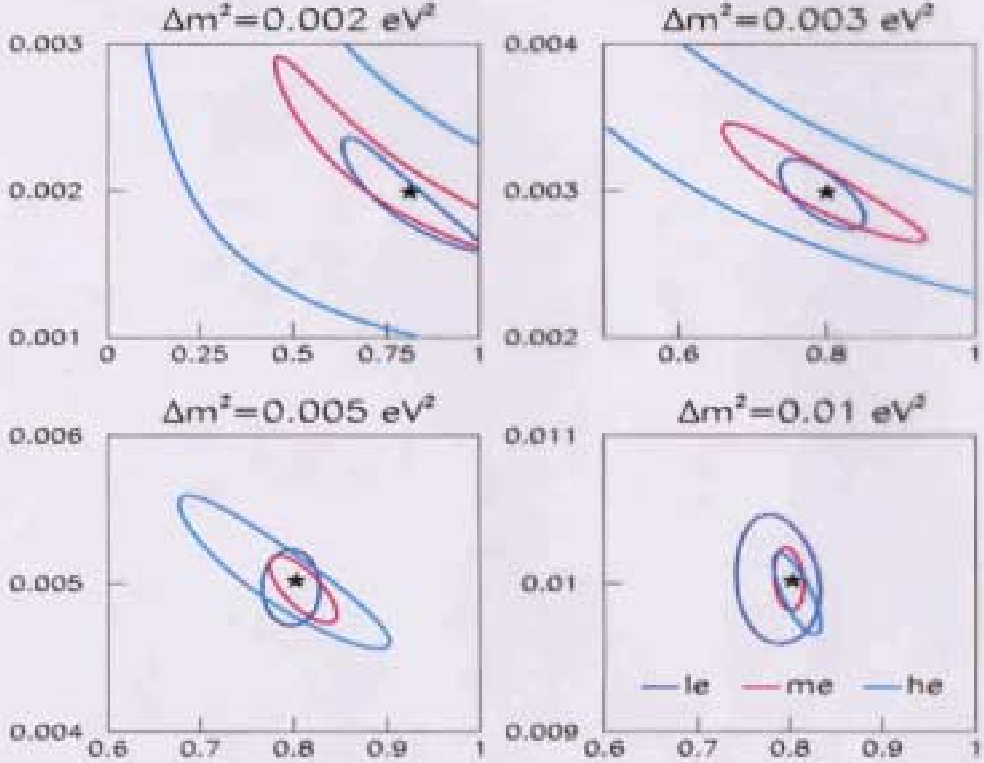
MINOS

Comparison of Different Beams



CC Energy Spectru
68% Contours
10kt-yr exposure

Wojcicki - 1

S. Wojcicki, Neutrino2000

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MINOS

Neutrino 2000
June 17, 2000
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Schedule

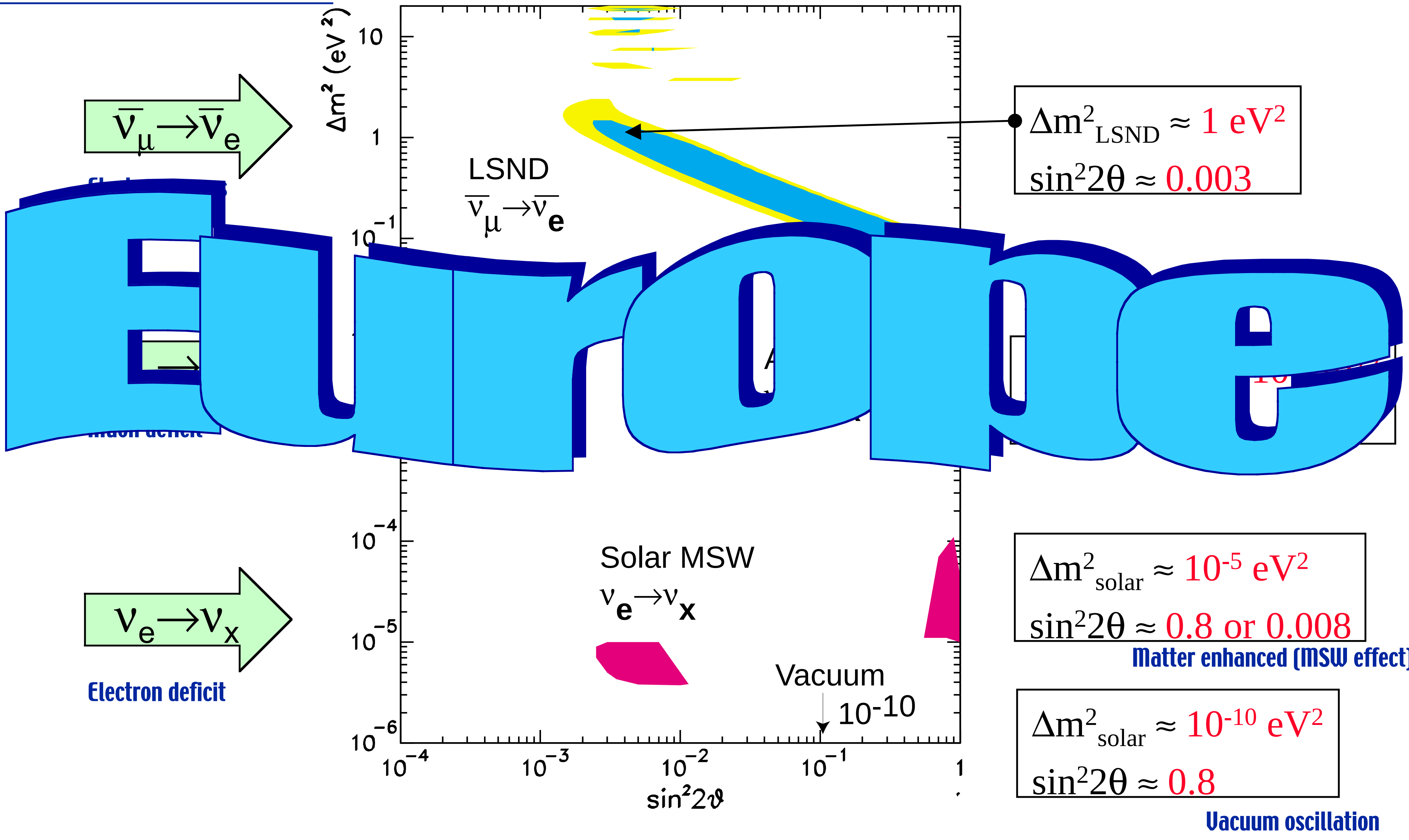
- September, 2000 – Soudan Cavern Excavation Complete
- October, 2000 – Start of Scintillator Module Production
- March, 2001 - Start of Far Detector Installation
- September, 2002 – Completion of 1st MINOS SuperModule
- October, 2002 –Start of Installation of Beam Components and Near Detector
- June, 2003 – Start of System Commissioning
- July, 2003 – Completion of Detector Installation
- October, 2003 – Start of Physics Data Taking

Wojcicki - 28

S. Wojcicki, Neutrino2000

Oscillation map - “allowed regions”

Two-neutrino oversight



Detecting flavor oscillations by "appearance"

$$\nu_\mu \rightarrow \nu_\tau$$

$$\nu_\tau + N \rightarrow \tau + jet; \quad \tau \rightarrow \begin{cases} e\nu\nu & 18\% \\ \mu\nu\nu & 18\% \\ h^- n h^0 \nu & 50\% \\ h^- h^+ h^- n h^0 \nu & 14\% \end{cases}$$

Charged current (CC)

1. ***High energy neutrinos***
   ⇒ Sufficient energy to produce heavy tau (m_τ = 1777 MeV)
2. ***Detector capable of identifying tau lepton***
   ⇒ Detect the decay products and missing momentum from neutrinos
   ⇒ or look for tau track (≈1 mm length) to see "kink"

$$\nu_\mu \rightarrow \nu_e$$

$$\nu_e + N \rightarrow e + jet$$

Charged current (CC)

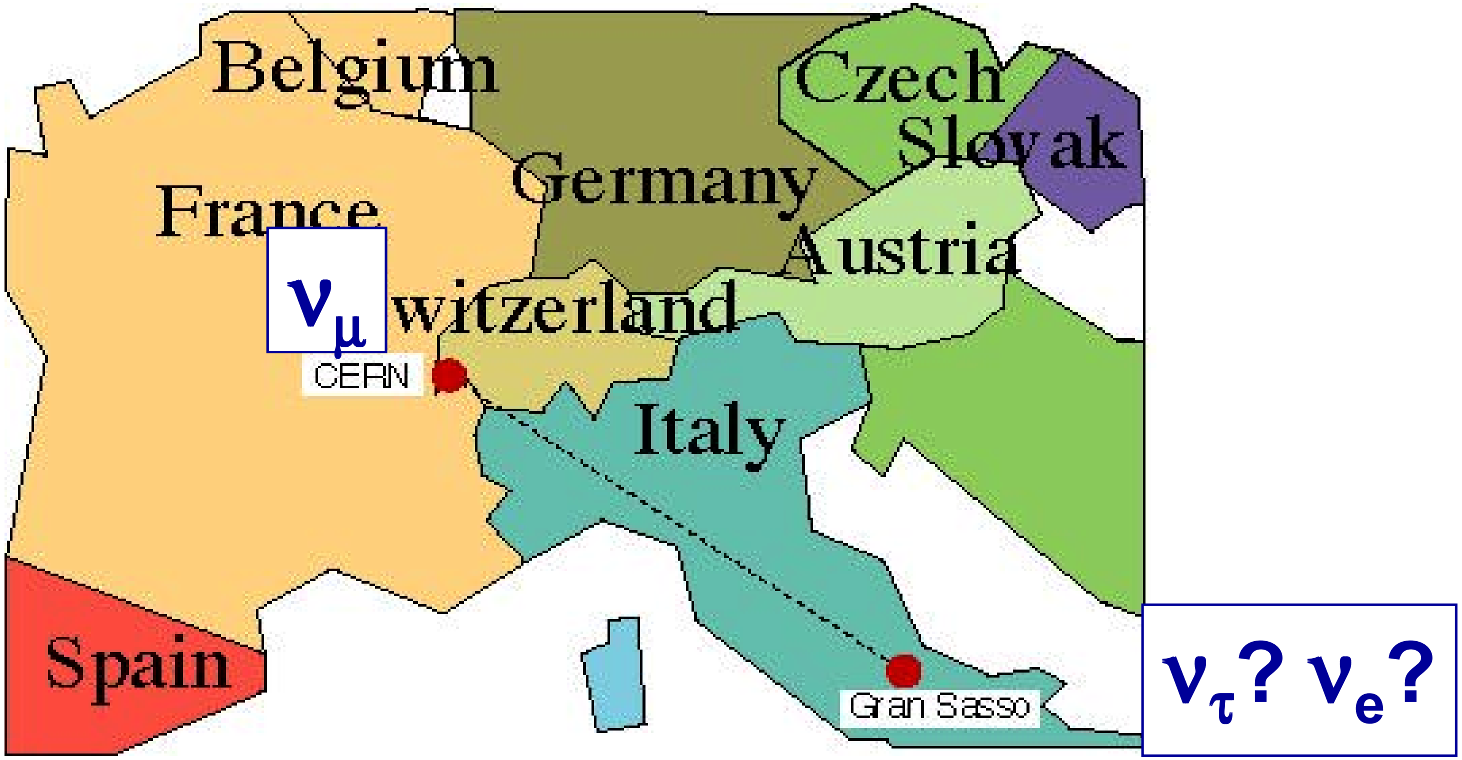
1. ***Excellent electron identification***
   ⇒ high granularity for e/π^0 separation

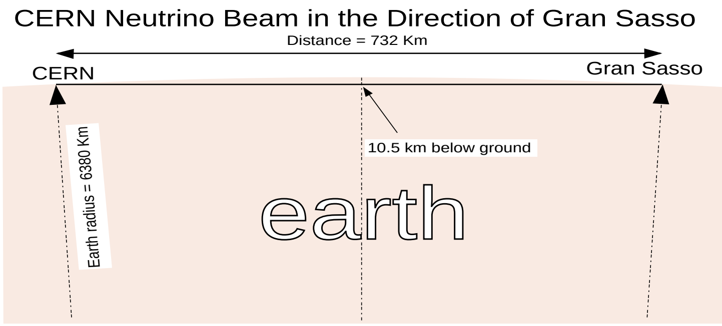
⇒ in general, difficult tasks for large detectors!

CNGS neutrino beam

The expected ν_e and ν_τ contamination of the CNGS beam are of the order of 10^{-2} and 10^{-7} respect to the dominant ν_μ.

CERN 98-02 - INFN-AE/98-05
CERN-SL/99-034(DI) - INFN/AE-99/05





Planned beam commissioning: May 2005

CNGS event rates

- Primary protons: **400 GeV; 4x2.3x10^{13} p/cycle; 26.4 s/cycle**
- Pots per year: **4.5x10^{19} pots** "shared"; **200x0.75 days/year**

Process	Rates (events/kton/year)
ν_μ CC	**2450**
$\bar{\nu}_\mu$ CC	**49**
ν_e CC	**20**
$\bar{\nu}_e$ CC	**1.2**
ν NC	**823**
$\bar{\nu}$ NC	**17**

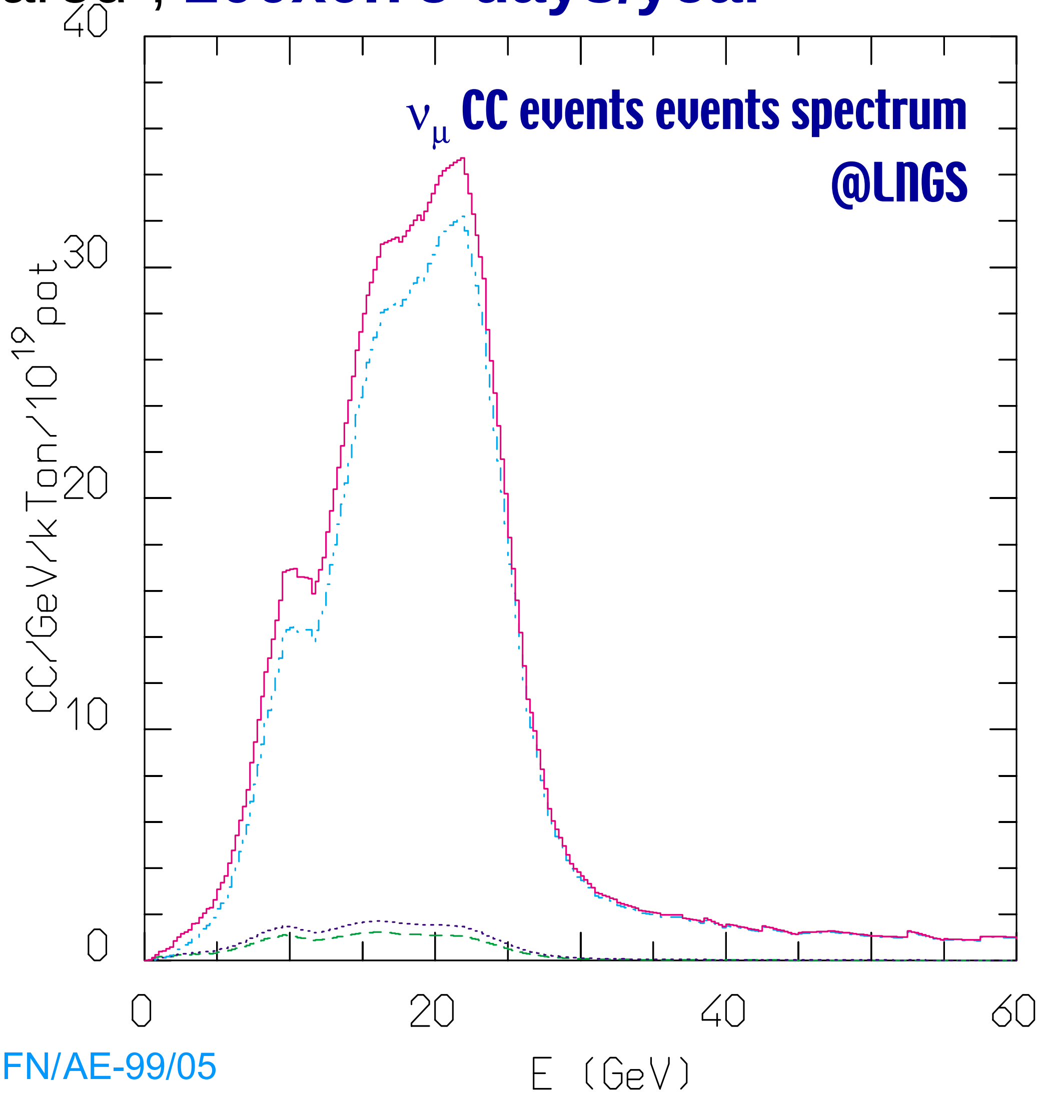
No oscillations

- Optimized for $N_\tau \propto \int \phi_{\nu_\mu}(E) \times \sigma^{CC}_{\nu_\tau}(E) E^{-2} dE$

Δm^2 (eV^2)	**Rates (events/kton/year)**
1×10^{-3}	2.4
2.5×10^{-3}	15.1
3.5×10^{-3}	29.4
5×10^{-3}	58.6
1×10^{-2}	209.0

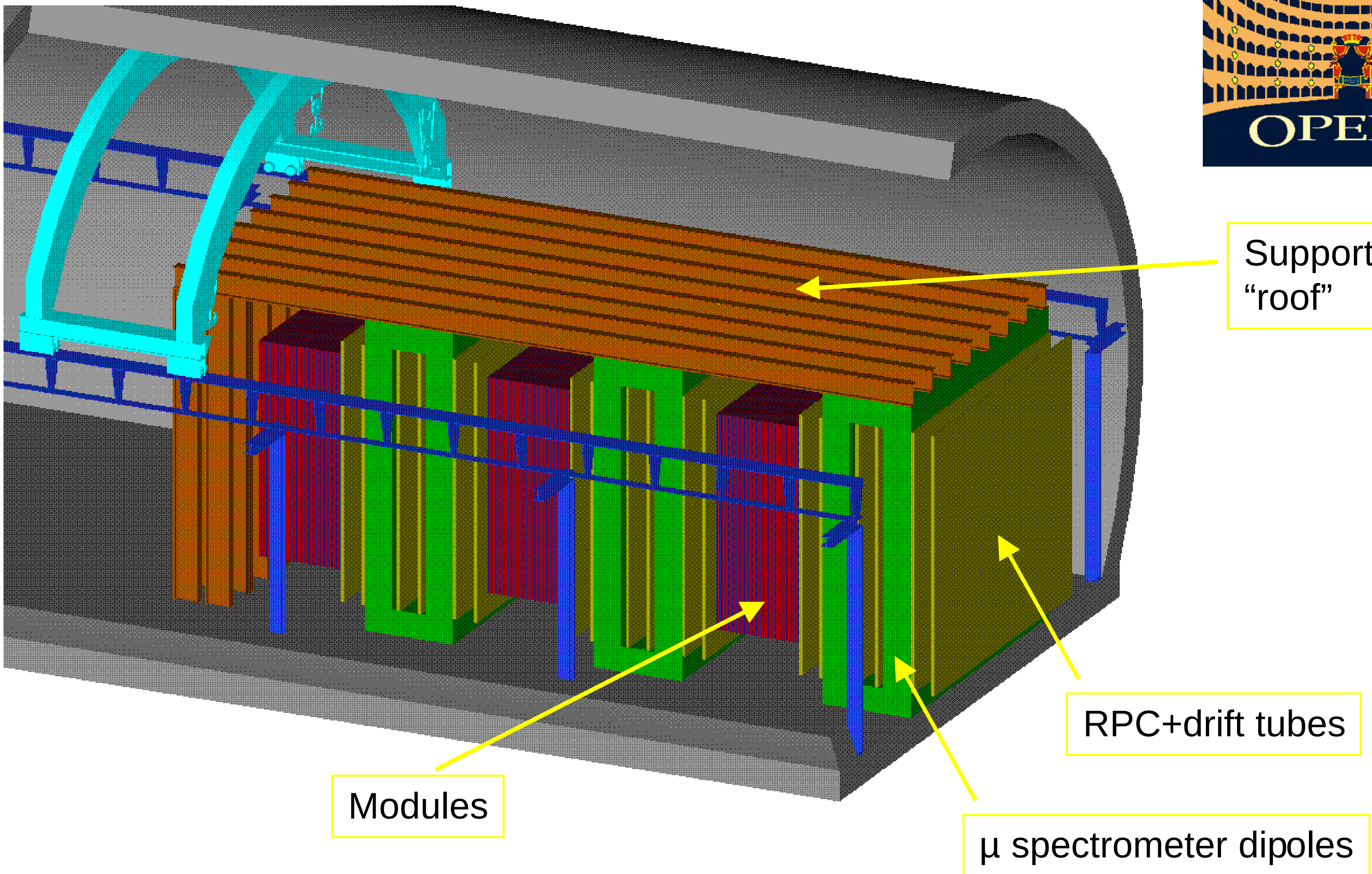
ν_τ CC event rates

- 7.6x10^{19} pots/yr "dedicated"



CERN 98-02 - INFN-AE/98-05; CERN-SL/99-034(DI) - INFN/AE-99/05

OPERA baseline design

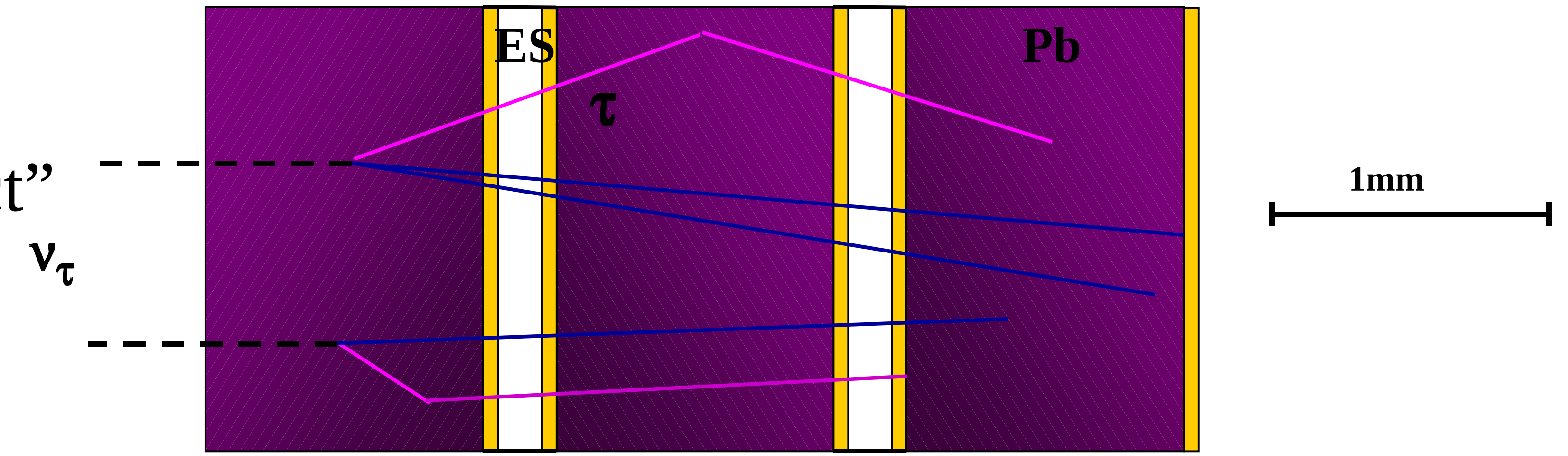


OPERA design is “LNGS Hall independent”

OPERA ECC elementary cell

***Direct* detection of τs by decay topology (γcτ ~ 1mm)**

Baseline option: "compact"



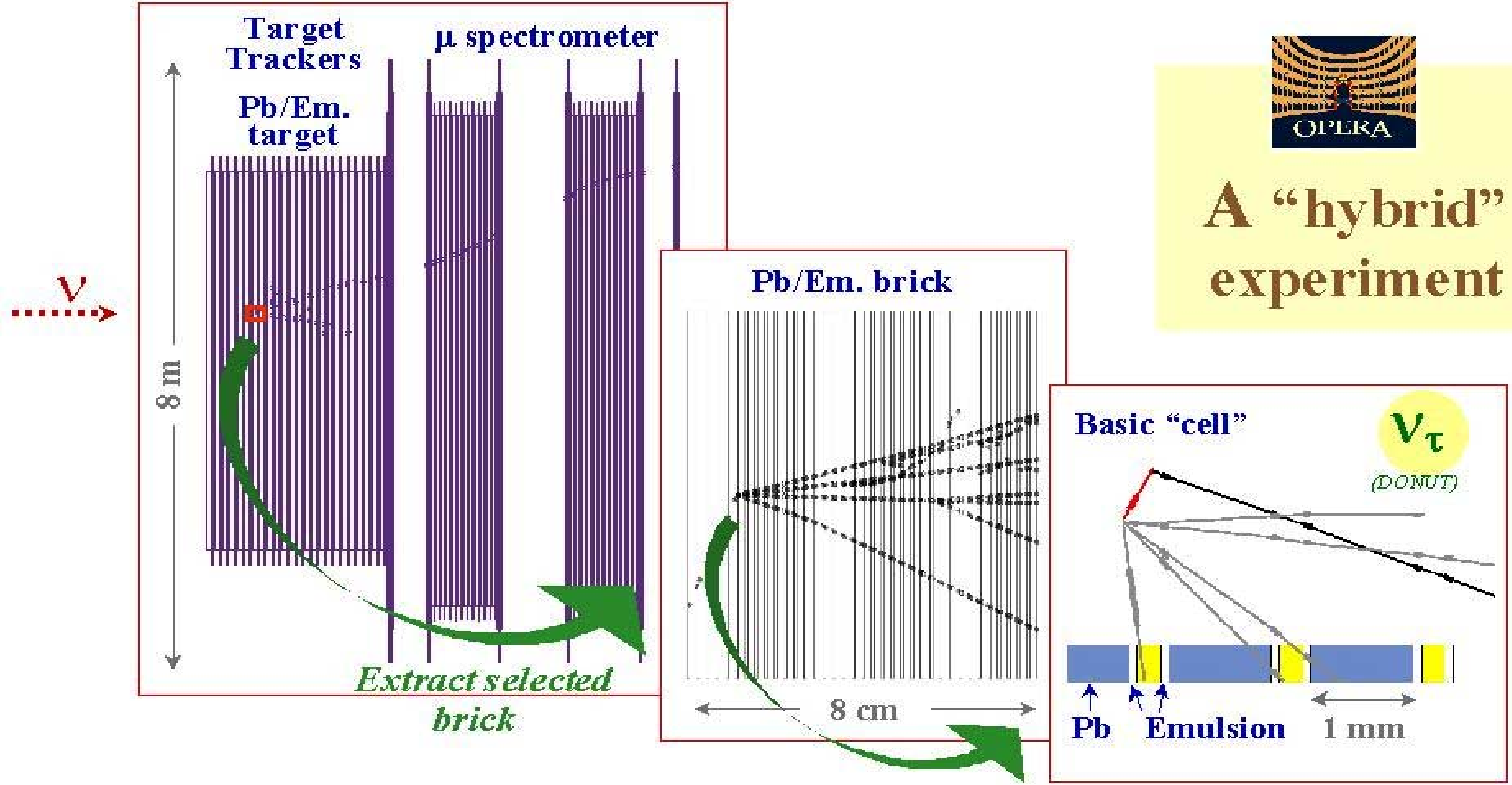
Basic ECC (Emulsion Cloud Chamber) concept:

Passive target material and emulsion tracking

large mass — high space resolution

Prototype: Measured angular and position resolution with 100 μm segments: ~2 mrad in angle and ~0.6 μm in position

A “hybrid” experiment



Electronic detectors

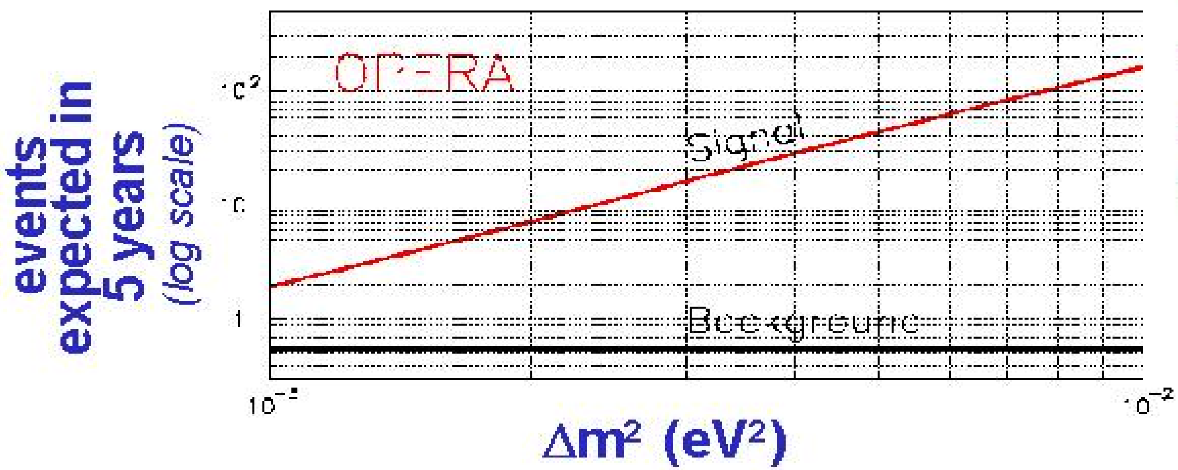
- → select ν interaction brick
- → μ ID, charge and p

Emulsion scanning

- → vertex search
- → decay search
- → e/γ ID, kinematics

Expected numbers of events

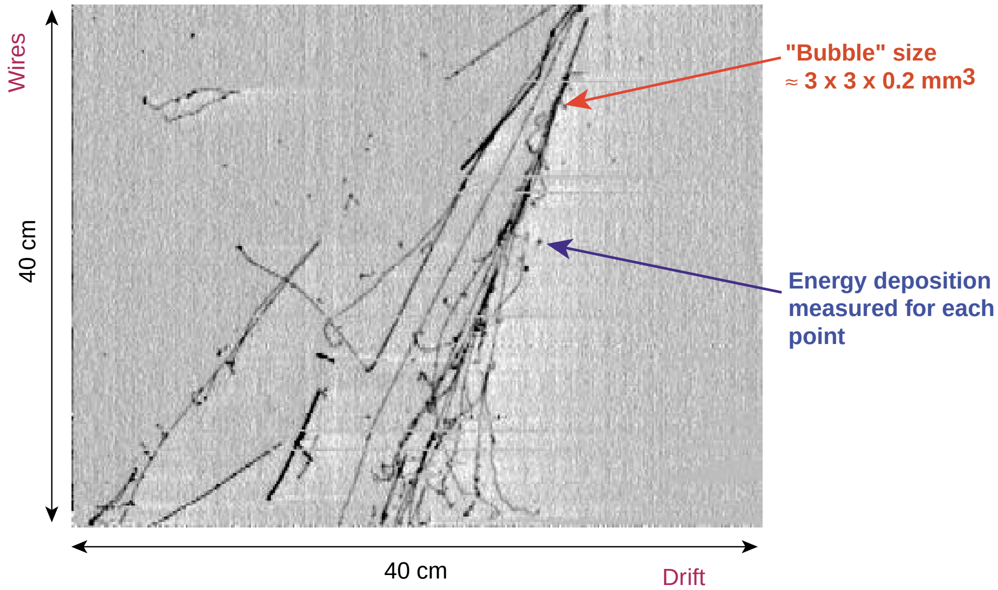
τ decay	ν_τ events Δm^2 (10^{-3} eV^2) 1.5	3.2	5.0	b.g.
e	1.7	7.7	18.5	0.19
μ	1.3	5.7	13.8	0.13
h	1.1	4.9	11.8	0.25
Total	**4.1**	**18.3**	**44.1**	**0.57**

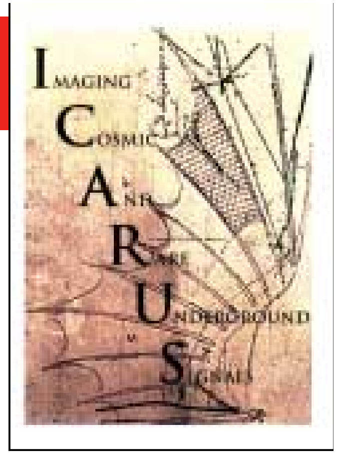


- **Full mixing**
- **5 years with shared SPS operation (2.25×10^{20} pot)**
- **Average target mass = 1.8 kton**

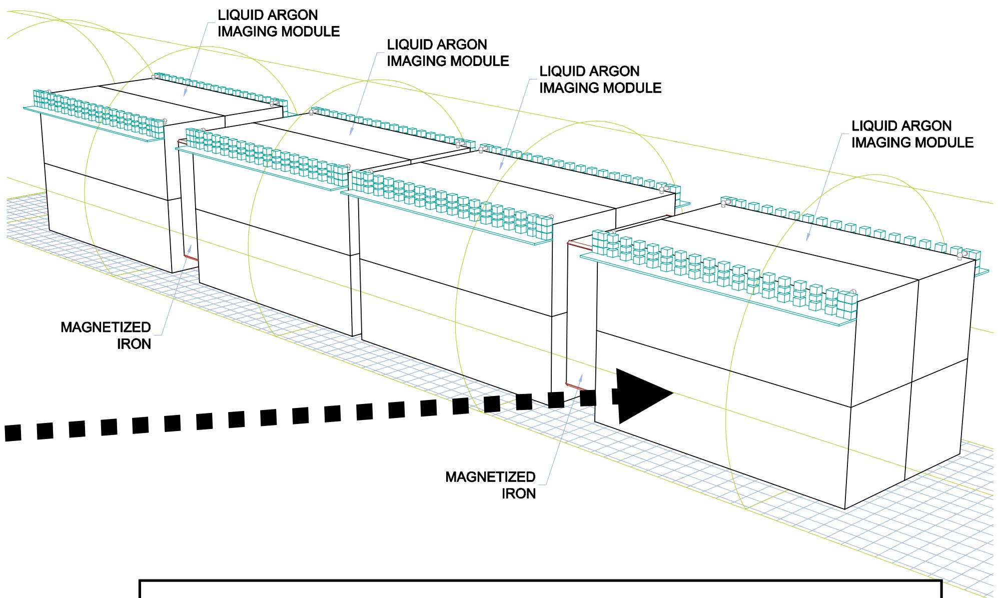
  (accounting for mass reduction with time, due to brick removal for analysis)
- **Uncertainties on background and efficiencies accounted for in the following**

The ICARUS experiment

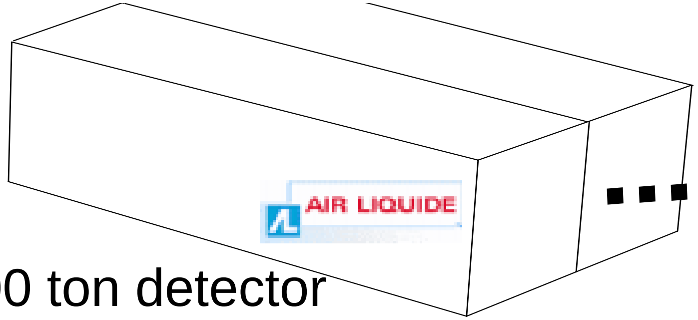




ICARUS 5kt (proposed)



ICARUS T600 (approved)



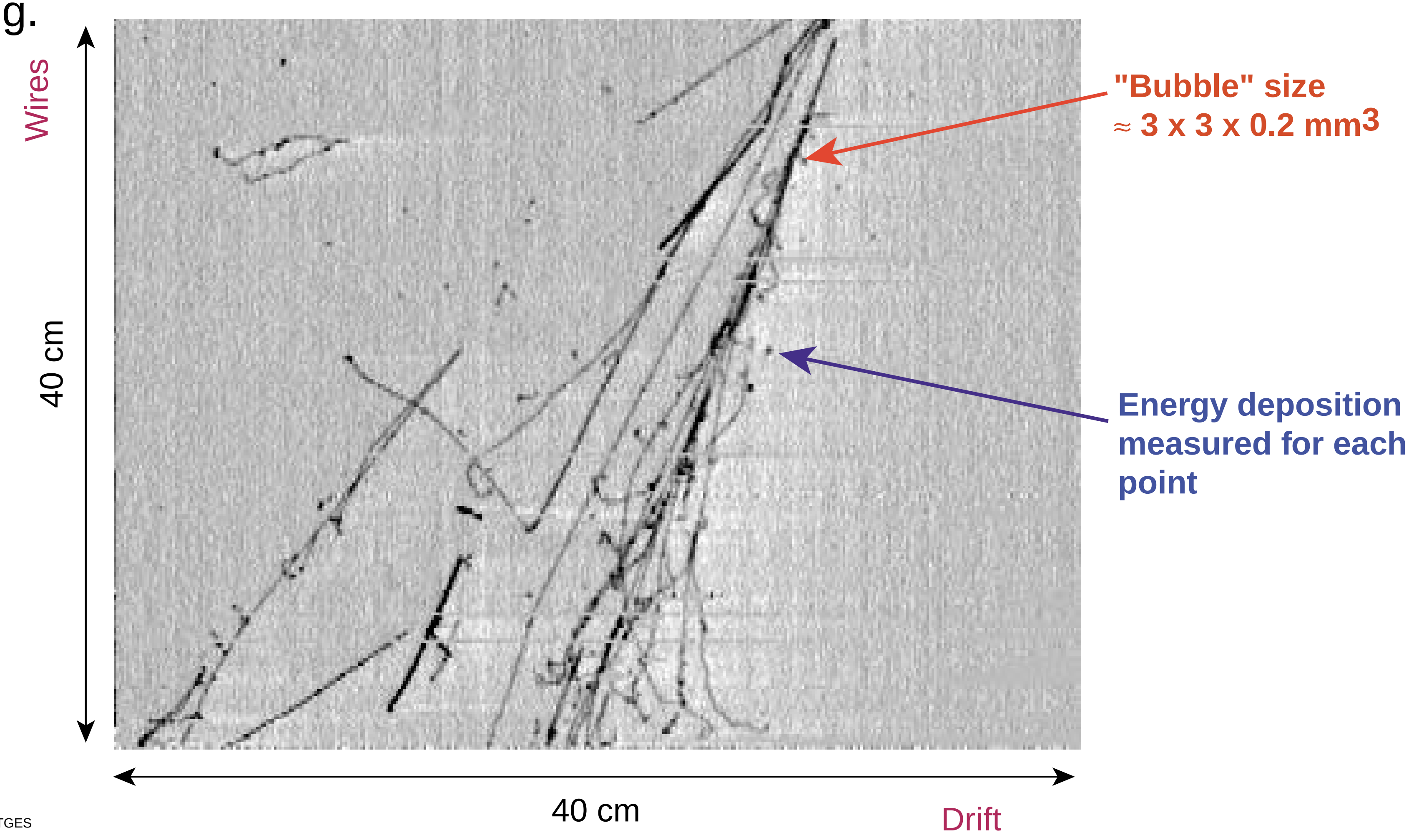
600 ton detector

First test run in March 2001!
In LNGS Tunnel in 2002

Two possible options:
A) ≈8 x T600
B) 4 x T1400 (better for physics)

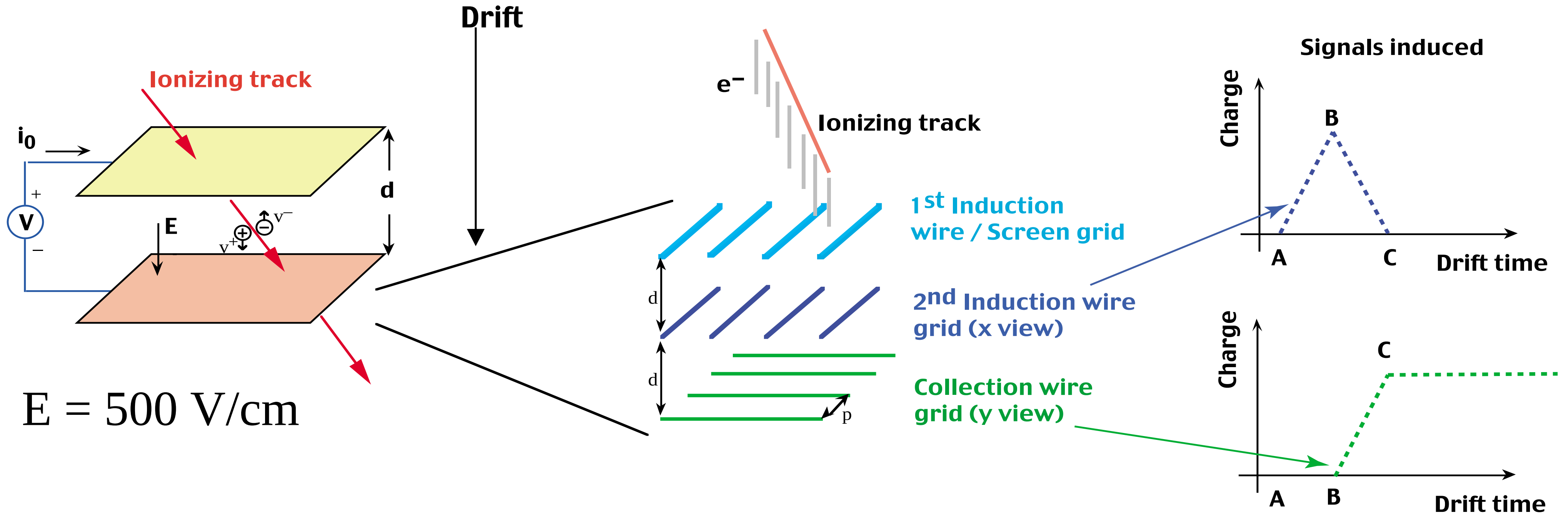
ICARUS liquid argon imaging TPC (I)

- The LAr TPC technique is based on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized (i.e. a set of fine pitch wire grids) it is possible to realize a massive "electronic bubble chamber", with superb 3-D imaging.



ICARUS liquid argon imaging TPC (II)

- Detect electrons produced by ionizing tracks crossing the LAr



Electron–ion pairs are produced
Electrons give the main contribution to the induced current due to the much larger mobility

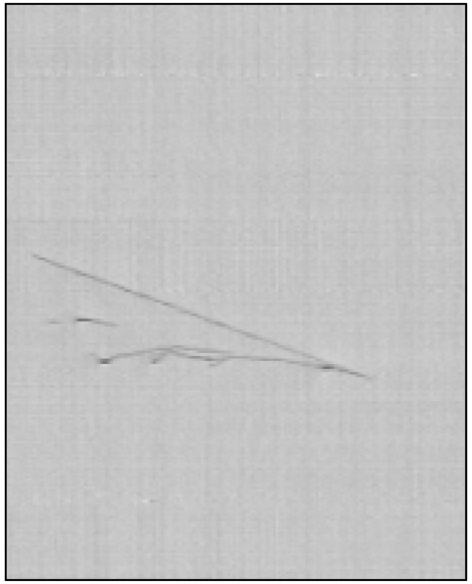
$I_0 = e(v^+ + v^-)/d$

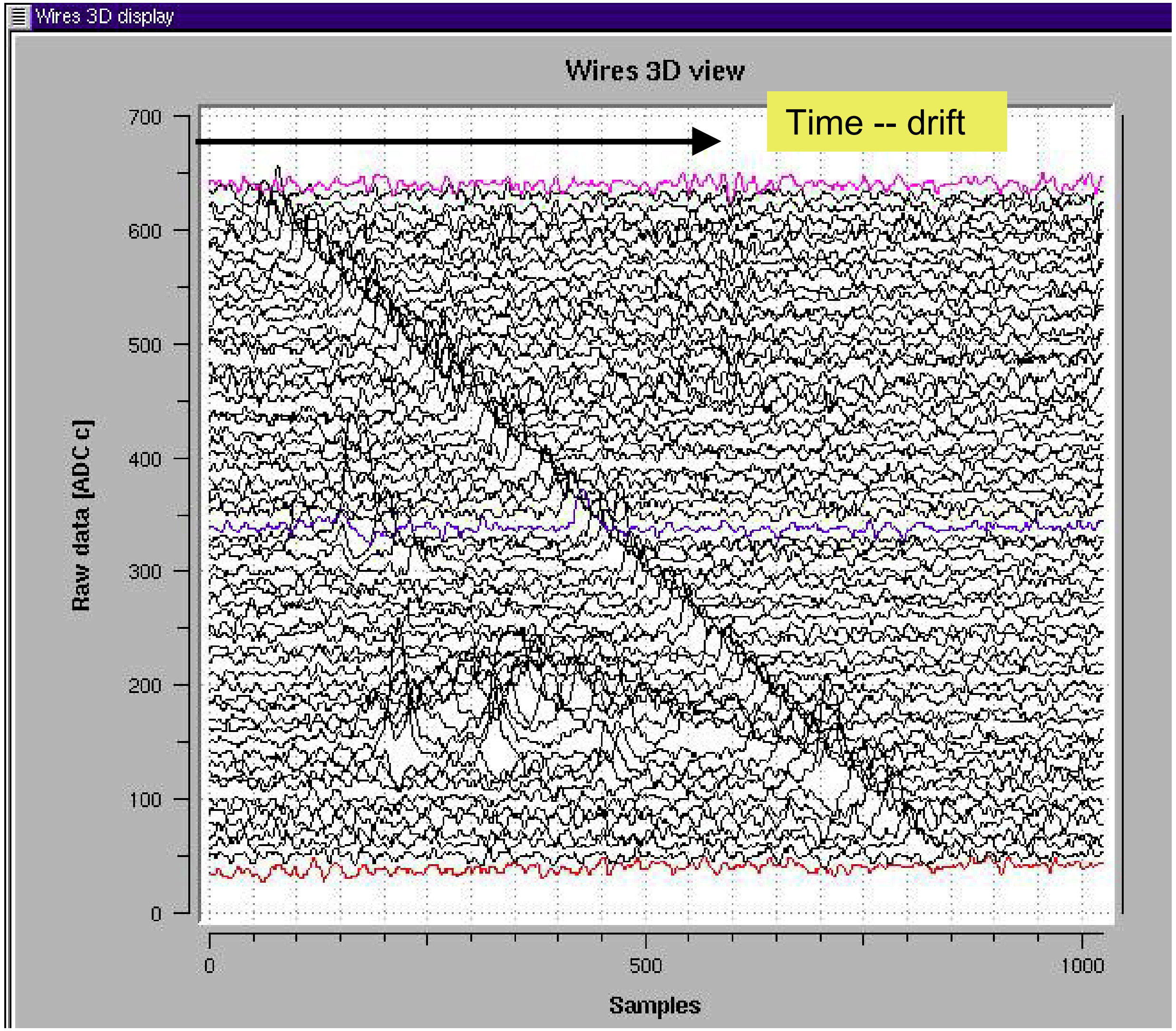
A set of wires at the end of the drift give a sampling of the track
No charge multiplication occurs near the wires Ë electrons can be used to induce signals on subsequent wires planes with different orientations ⇒ 3D imaging

ICARUS liquid argon imaging TPC (III)

Detector is continuously sensitive, thus allowing to easily simultaneously collect atmospheric, CNGS and other rare events...

Real event from 15 ton



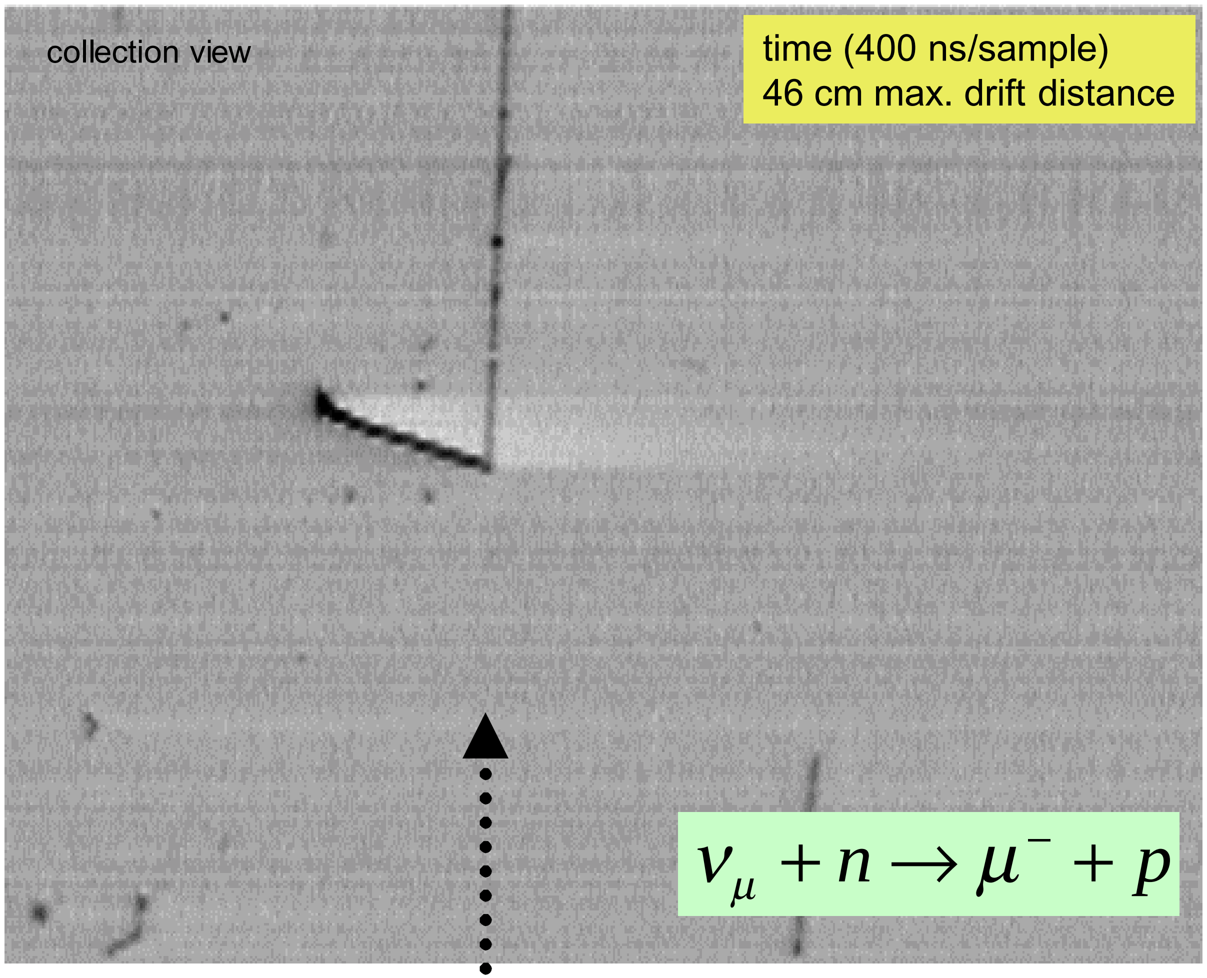


Neutrino event in 50 liter LAr TPC (1998)

ICARUS-CERN-Milano

In a pre-monolithic phase

128 readout wires
2.54 mm wire pitch



$$\nu_\mu + n \rightarrow \mu^- + p$$

CERN ν-beam

(Chamber located in front of NOMAD detector)

The MONOLITH proposal

Large mass ~ 35 kton

Magnetized Fe spectrometer B = 1.3 Tesla

Space resolution ~ 1 cm (rms on X-Y coordinates)

Time resolution ~ 1 ns (for up/down discrimination)

Momentum resolution $\sigma_p/p \sim$ 20% from track curvature for outgoing μ

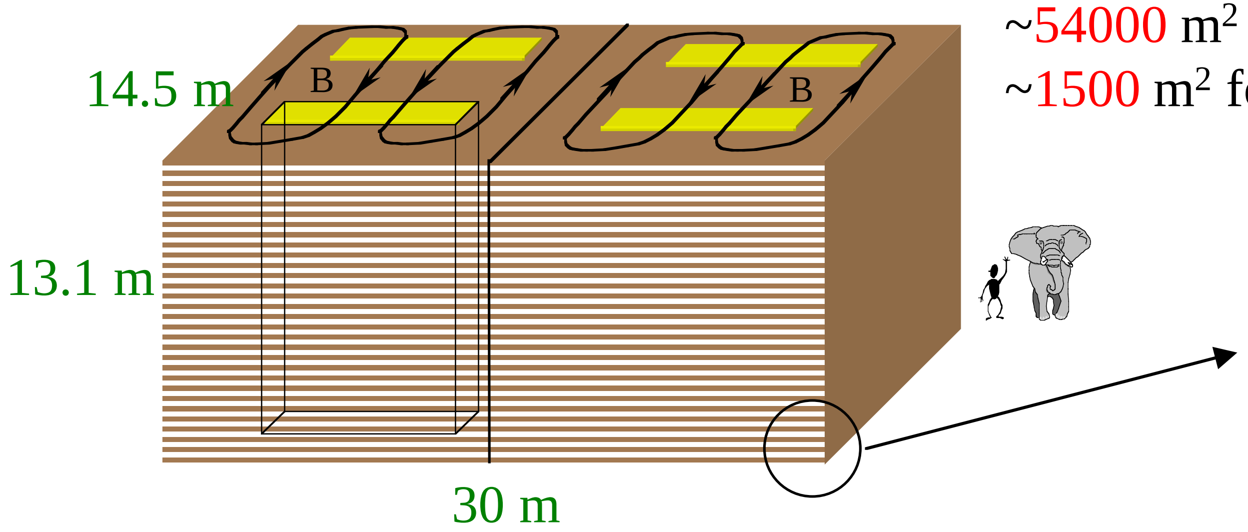
~ 6% from range for stopping muons

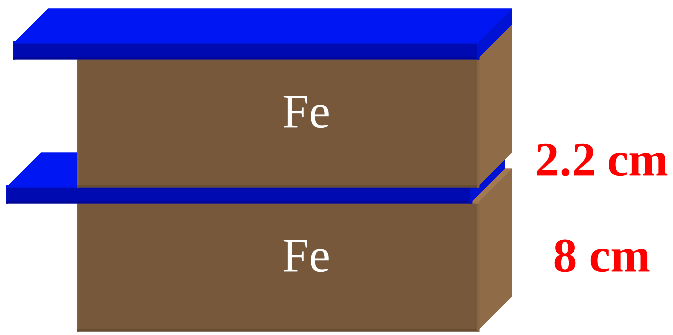
Hadron E resolution $\sigma_{E_h}/E_h \sim 90\%/\sqrt{E_h} \oplus 30\%$

8.0 x 3000 x 1500 cm^3 x 7.87 g/cm^3 = 285 ton/plane 120 planes

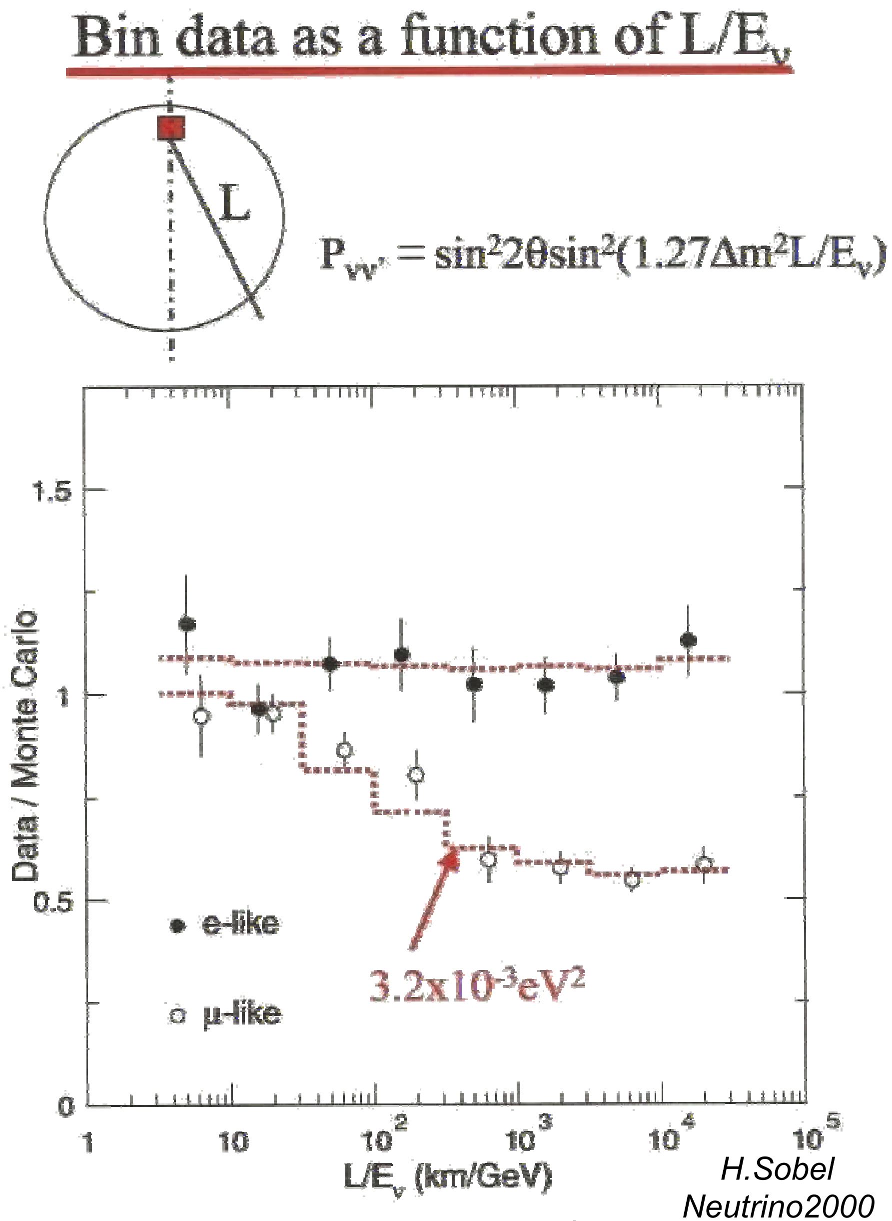
~54000 m^2 of detector : Glass Spark Counters

~1500 m^2 for external veto: Scintillator Counters





Oscillations?



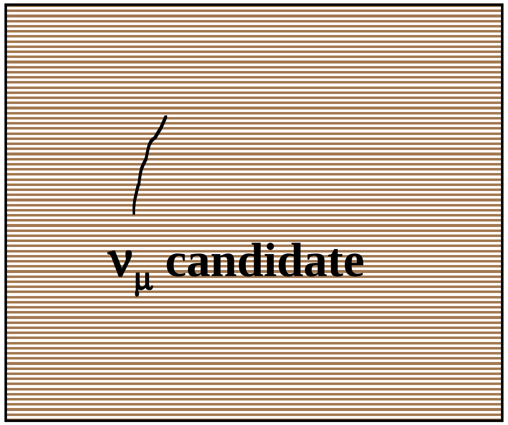
H.Sobel
Neutrino2000

$$P(\nu_\alpha \rightarrow \nu_\beta) \stackrel{?}{=} \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

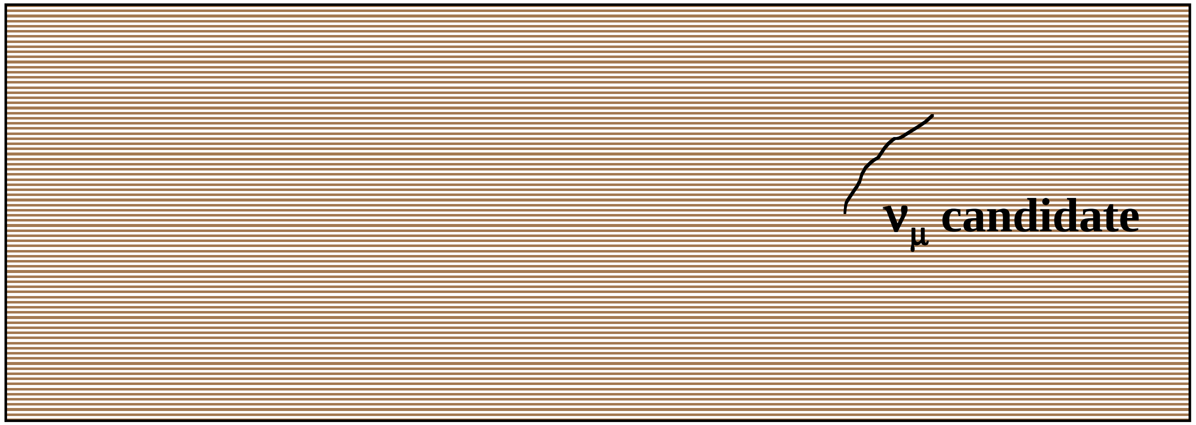
- The L/E resolution of SuperKamiokande is not good enough to detect oscillations.
- SuperKamiokande only sees a "deficit" with increasing L/E
- *"There is as yet no direct evidence of an oscillation pattern"*
  (J. Ellis, summary of Neutrino 2000)

Atmospheric neutrinos selection

Estimators: $\theta_\nu = \theta_\mu$ $E_\nu = E_\mu + E_h$



Y view



X view

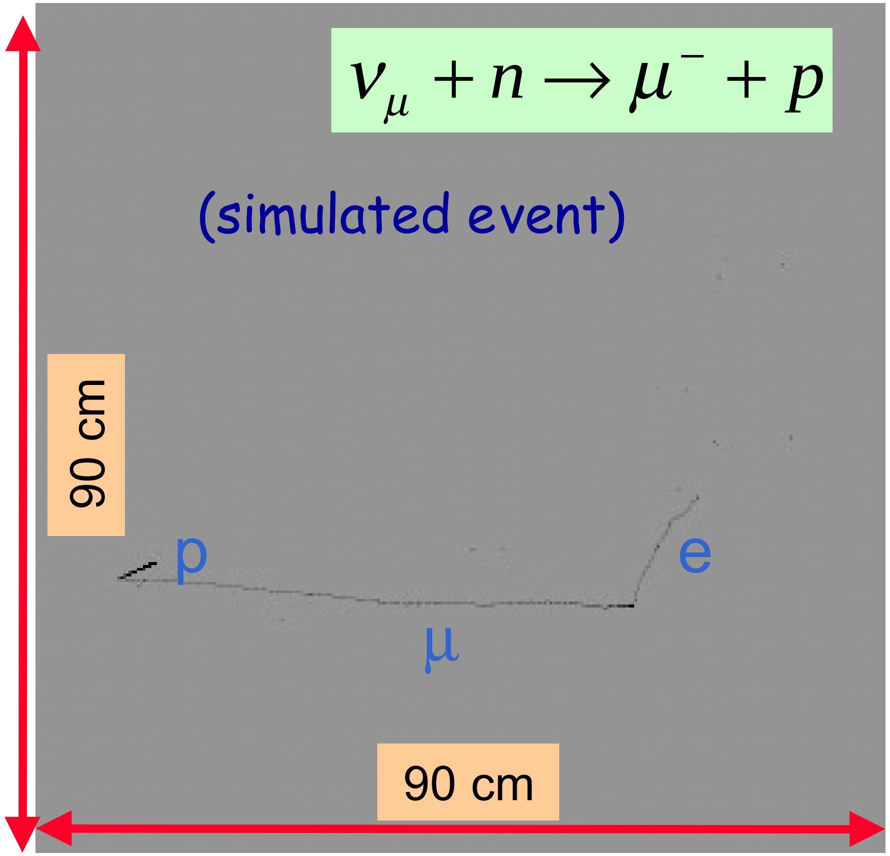
- ✓ Minimal requirements: p_μ > 1.5 GeV, Range(μ_{out}) > 4 m
- ✓ Selection on combinations of the observables E_μ, θ_μ, E_h to ensure the required *L/E* resolution
- ✓ Cuts on visible vertex coordinates and muon direction to reject cosmic muons background

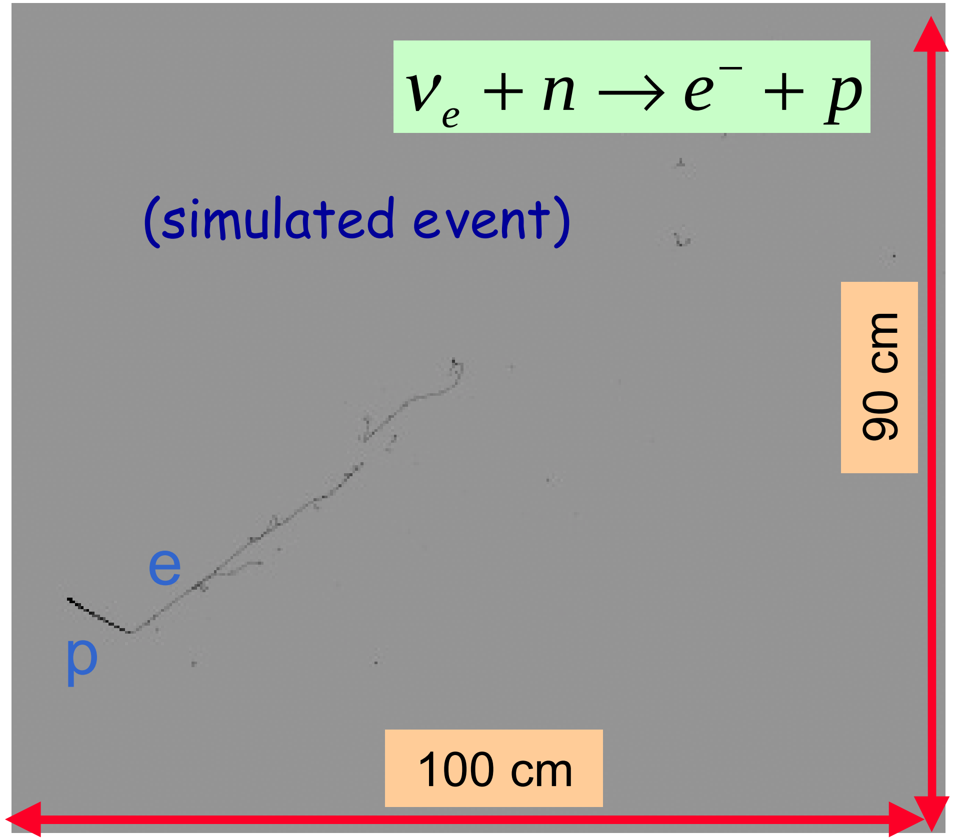
ICARUS event imaging

Estimators: complete final state event reconstruction

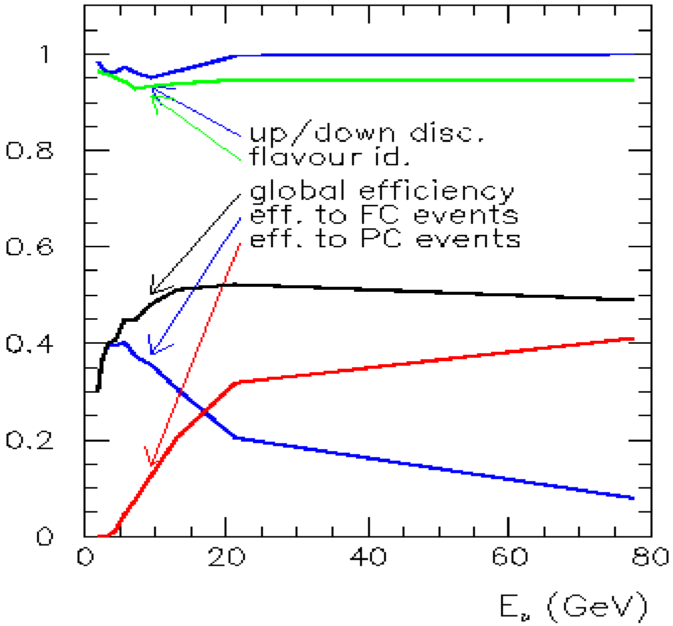
⇒incoming neutrino direction & energy reconstructed

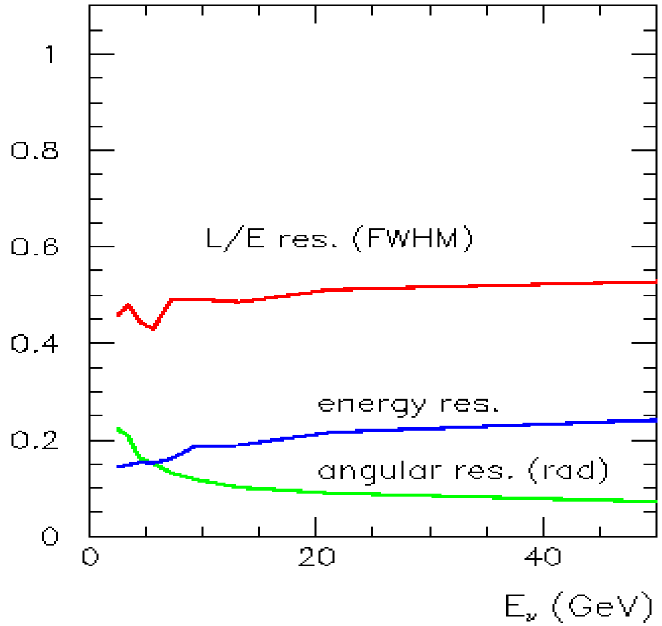
(dominated by Fermi motion at low E)





Efficiencies and resolutions



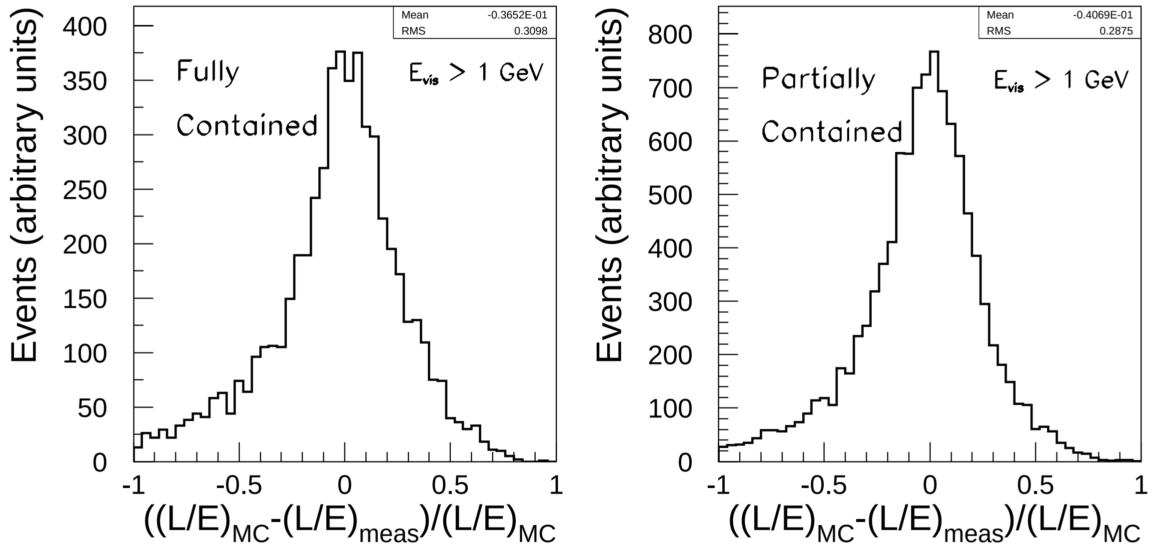


P. Antonioli
Now2000

Selected ν_μ CC (downgoing only!) after 4 years of data taking:

Fully contained:	931
Partially contained:	259
Total:	1190

ICARUS L/E selection



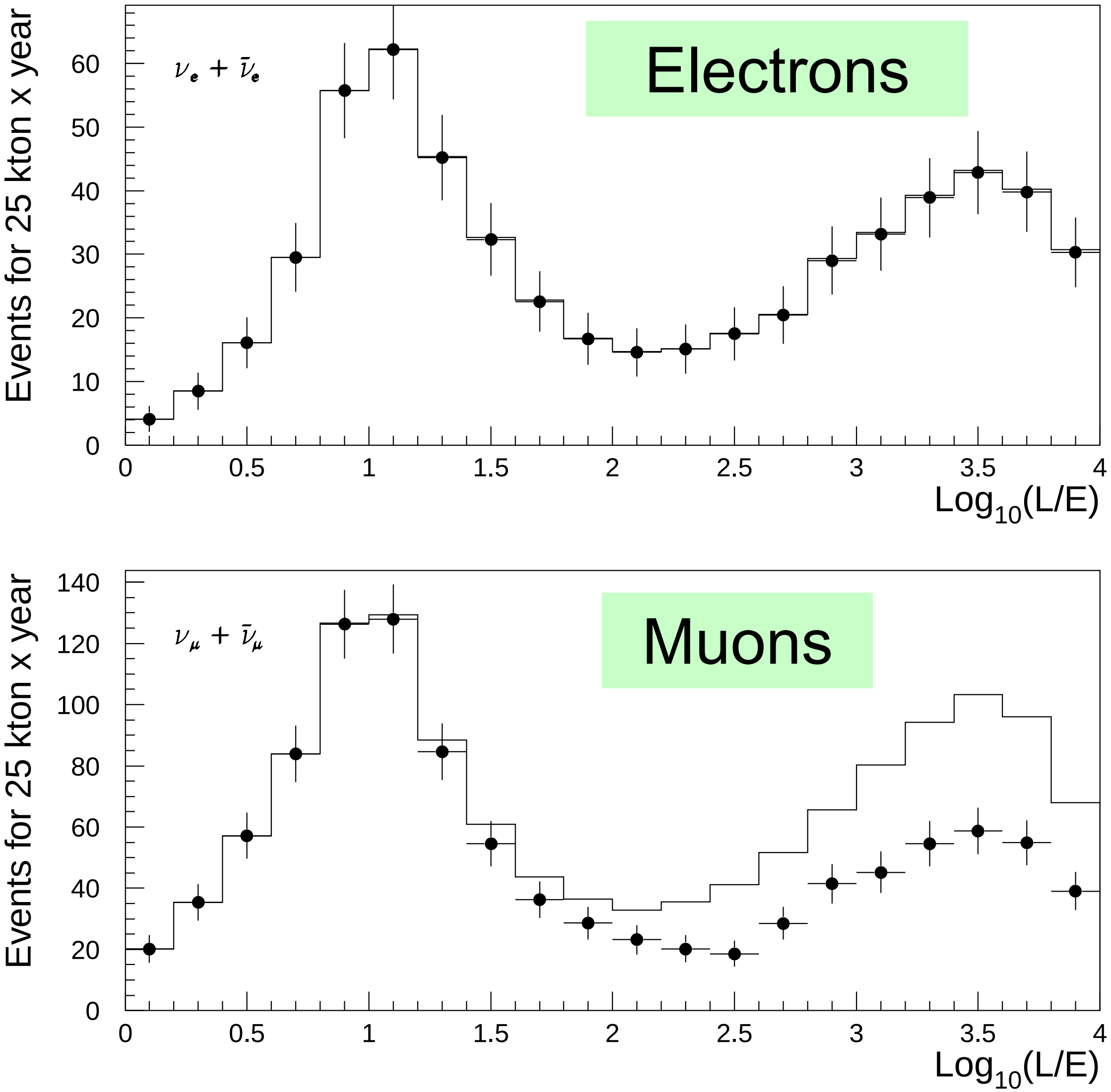
$$\Delta(L/E)_{RMS} \approx 30\%$$

- Selected ν_μ CC after 4 years of data taking:
- All muon-like events: 2700
- Evis>1 GeV: 1080 (to suppress Fermi motion effect)
- Total: 1080

It is not only a question of mass, but mass × efficiency!

Reference sample

25 kt x year



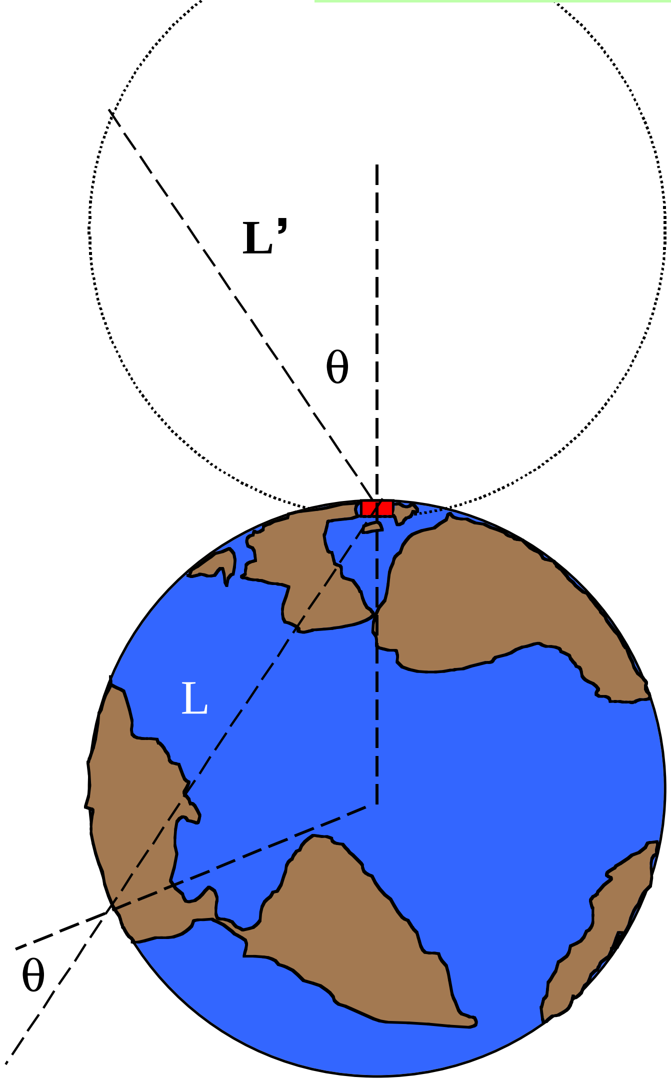
Excellent electron identification & measurement

Electron sample can be used as a reference for no oscillation case

- Oscillation parameters (3 family mixing):
  - → $\Delta m^2_{32} = 3.5 \times 10^{-3}\ eV^2$
  - → $\sin^2 2\Theta_{23} = 0.9$
  - → $\sin^2 2\Theta_{13} = 0.1$

Image method

MONOLITH can only see muons; it must do with them...



The disappearance probability can be measured with a single detector and two equal sources:

(equal source hypothesis only when geomagnetic effects are neglected ⇒ high energy)

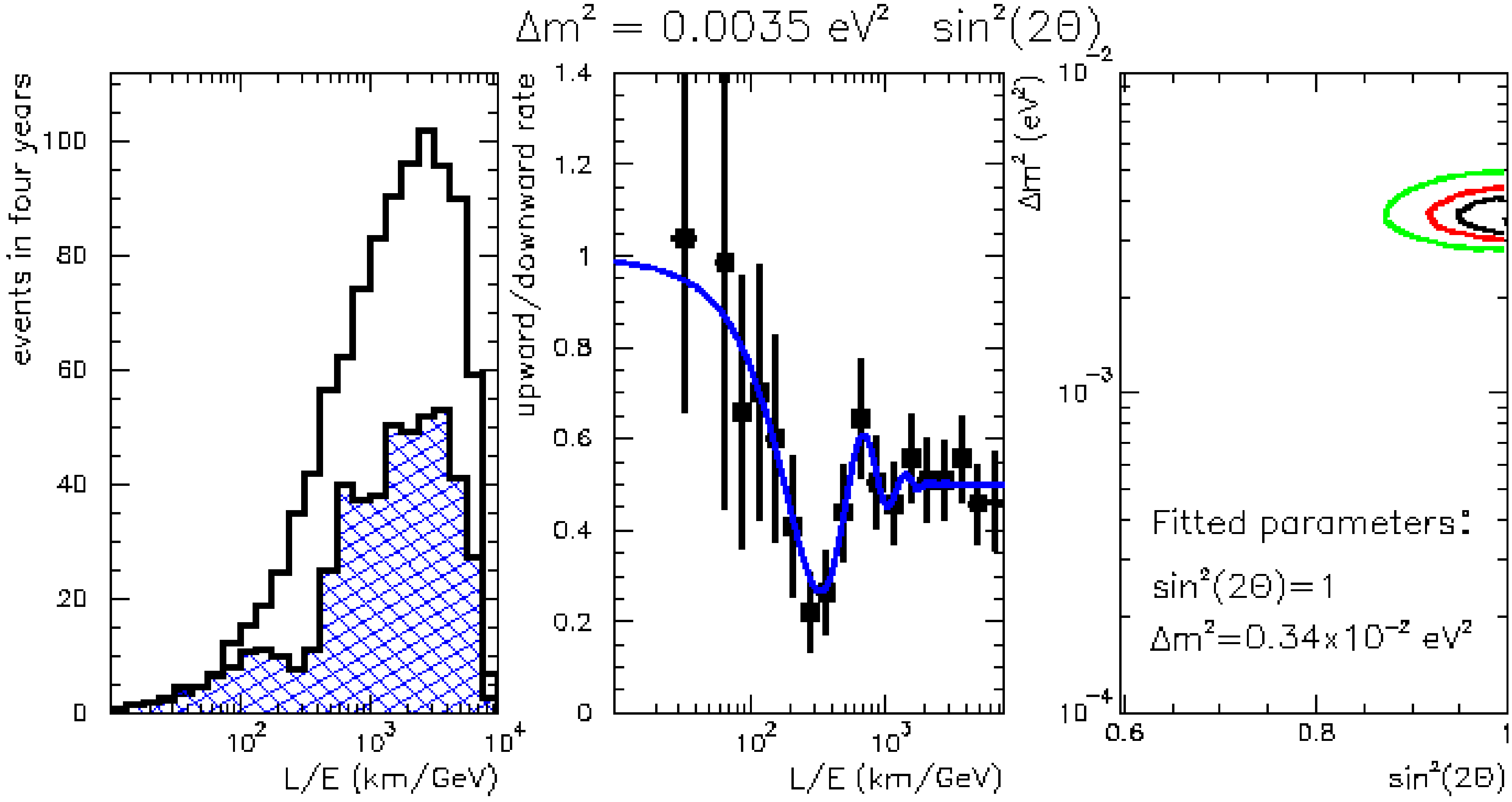
$L(\theta_{up}) = 2R\cos(\theta_{up}) \qquad L'(\theta_{down}) = L(\pi - \theta_{down})$

$$\frac{N_{up}(L/E)}{N_{down}(L'/E)} = P(\nu_\mu \rightarrow \nu_\mu; L/E)$$

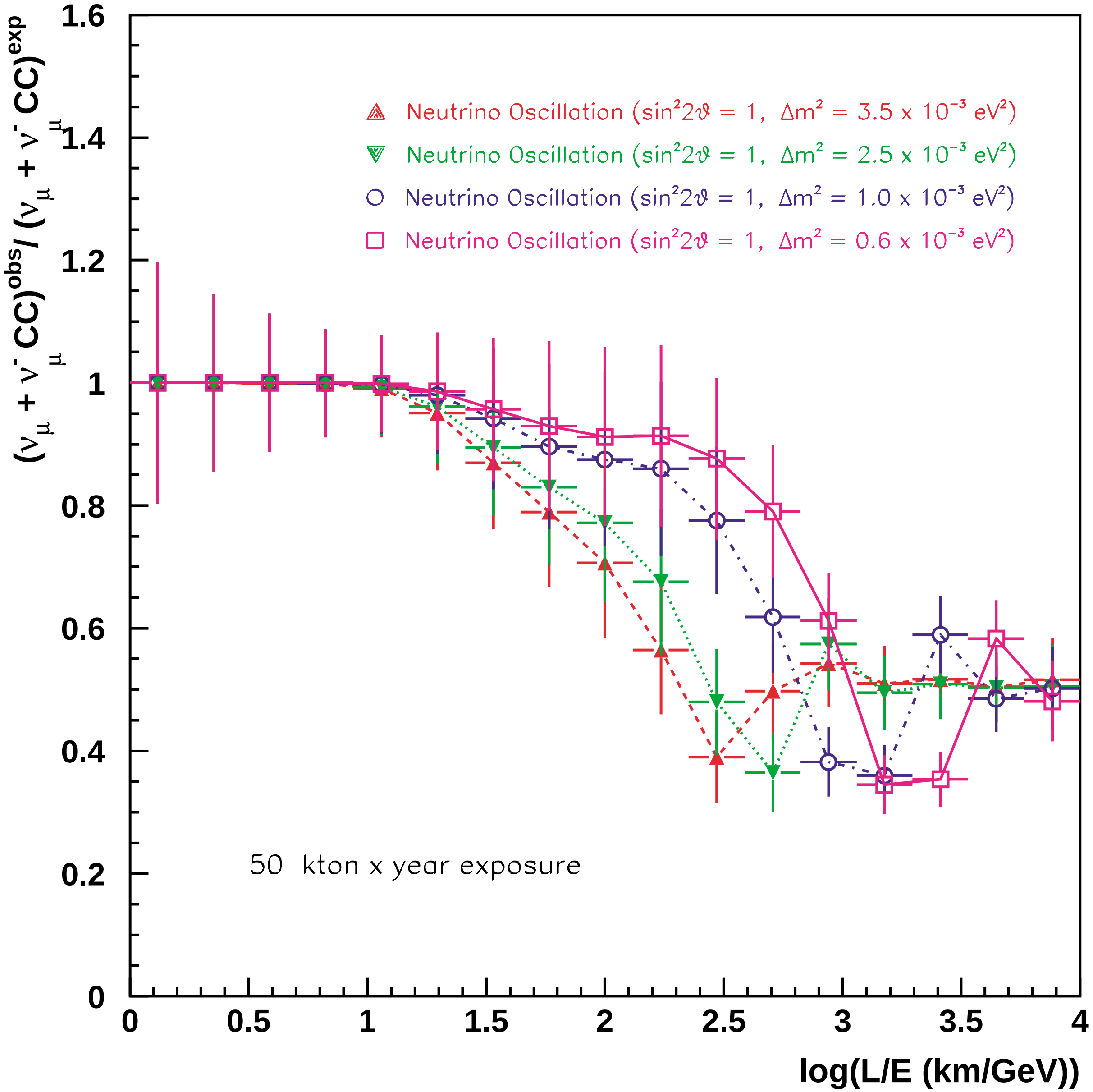
$$= 1 - \sin^2(2\Theta)\sin^2(1.27\,\Delta m^2\,L/E)$$

An *oscillation pattern* should appear in the experimental ratio of up to down fluxes

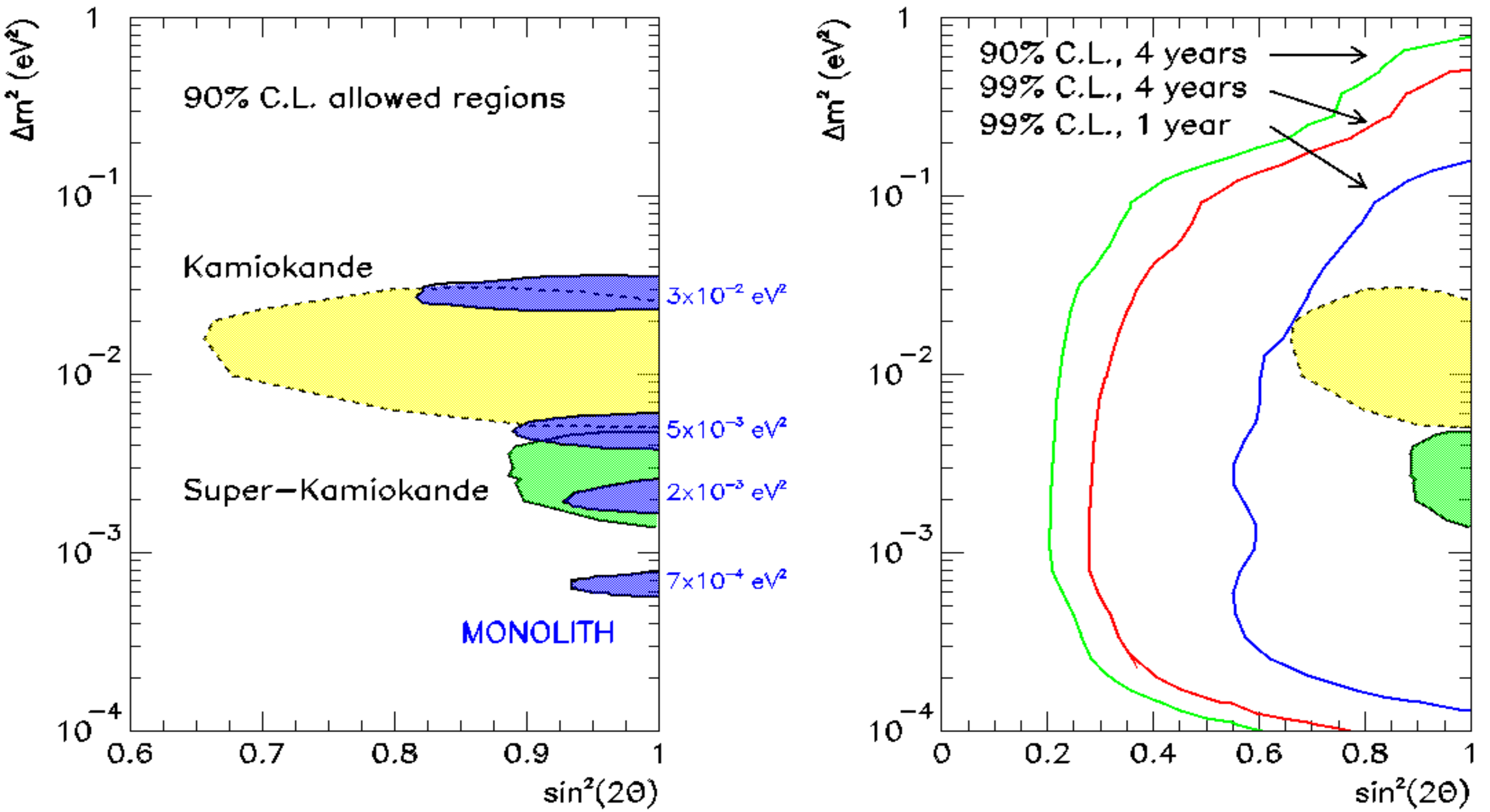
…after four years!



…after ten years!



MONOLITH sensitivity – 4 years



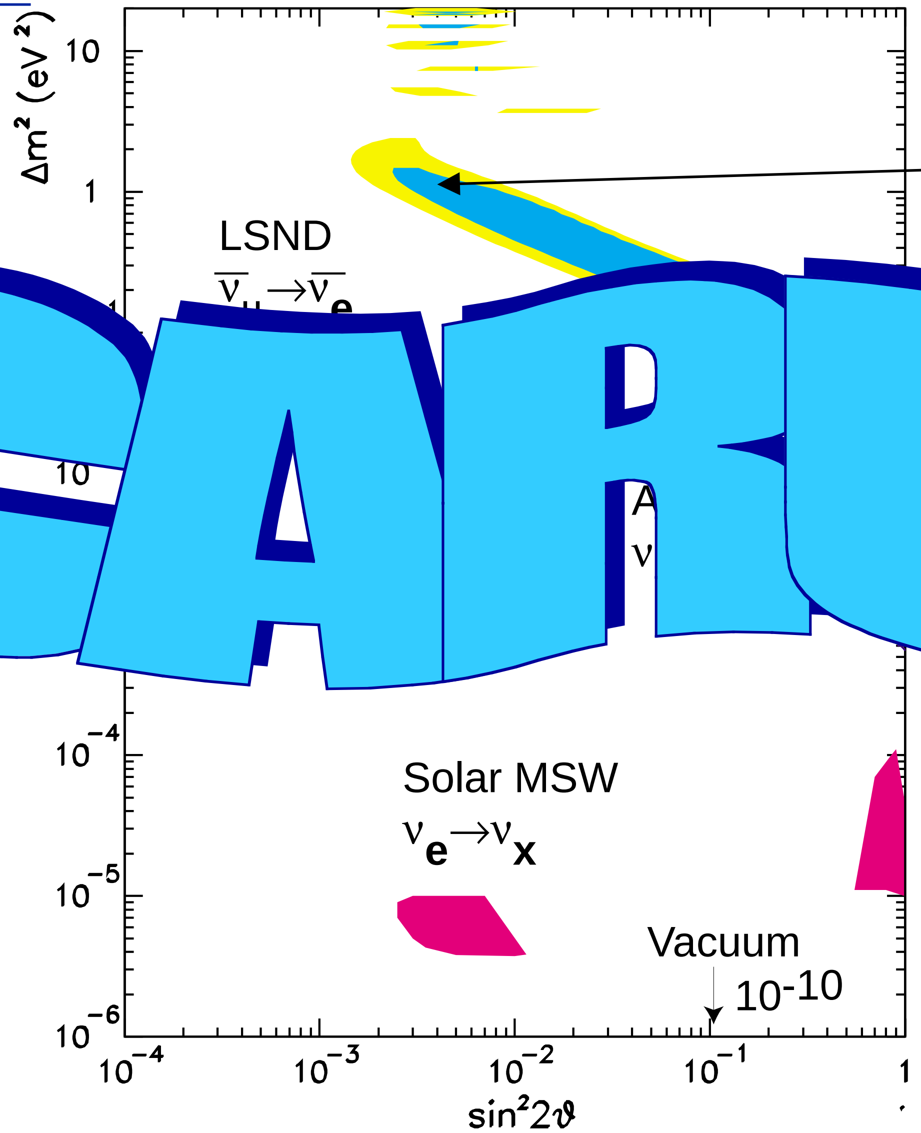
- Comparison of MONOLITH sensitivity to oscillations with Kamiokande and SuperKamiokande
- 90% C.L. allowed regions after 4 years for different Δm^2 (left)
- Exclusion regions if no effect is found (right)

Oscillation map - “allowed regions”

Two-neutrino oscillation

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

Electron excess



ICARUS

$\Delta m^2_{LSND} \approx 1\ eV^2$

$\sin^2 2\theta \approx 0.003$

$\nu_e \rightarrow \nu_x$

Electron deficit

$\Delta m^2_{solar} \approx 10^{-5}\ eV^2$

$\sin^2 2\theta \approx 0.8$ or 0.008

Matter enhanced (MSW effect)

$\Delta m^2_{solar} \approx 10^{-10}\ eV^2$

$\sin^2 2\theta \approx 0.8$

Vacuum oscillation

ICARUS physics potential (I)

Atmospheric neutrinos

- **Improvements over existing detection technique**
  - —*Detection down to production thresholds*
  - —*Complete event final state reconstruction*
  - —*Identification all neutrino flavors*
  - —*Identification of neutral currents*

$\Delta m^2_{32}, \quad \theta_{23}$

Δm^2_{12}

- **Excellent resolution on L/E reconstruction**
- **Direct τ appearance search**

Neutrinos from CERN

- **Search for $\nu_\mu \rightarrow \nu_\tau$**
- **Search for $\nu_\mu \rightarrow \nu_e$**

$\Delta m^2_{32}, \quad \theta_{23}, \quad \theta_{13}$

Solar neutrinos

- **Energy threshold: 5 MeV**
- **Large statistics, high precision measurements**
- **Experimental signal**

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

$\nu_e + {}^{40}Ar \rightarrow e + {}^{40}K^*$

Absorption

$\nu_e + e \rightarrow \nu_e + e$

Elastic

ICARUS physics potential (II)

Proton decay

- Large variety of decay modes accessible

  ⇒ *study branching ratios free of systematics*

- Background free searches

  ⇒ *linear gain in sensitivity with exposure*

Physics at Unification scales?

$$m_\nu \overbrace{=}^{?} \frac{m}{M_{heavy}}$$

Neutrinos "factory"

- Precise measurement of Δm^2_{23}, Θ_{23}, Θ_{13}
- Matter effects, sign of Δm^2_{23}
- First observation of $\nu_e \rightarrow \nu_\tau$
- CP violation

Δm^2_{32}, θ_{23}, θ_{13}

$\Delta m^2_{32}>0$ or $\Delta m^2_{32}<0$?

Unitarity of mixing matrix

$\delta \neq 0$?

ICARUS: a graded strategy

✓ **After several years of R&D and prototyping, the ICARUS collaboration is now realizing the first 600 ton module, which will be installed at Gran Sasso in the year 2001.**

Lab activities:

Small-scale prototypes → **15 ton** → **T600** **2x300 ton** ⇢ **T1400 (?)** **≈4x300 ton or 1x1400 ton**

We are here!

Cooperation with specialized industries:

→ **Air Liquide** for Cryostat and Argon purification

→ BREME Tecnica for internal detector mechanics

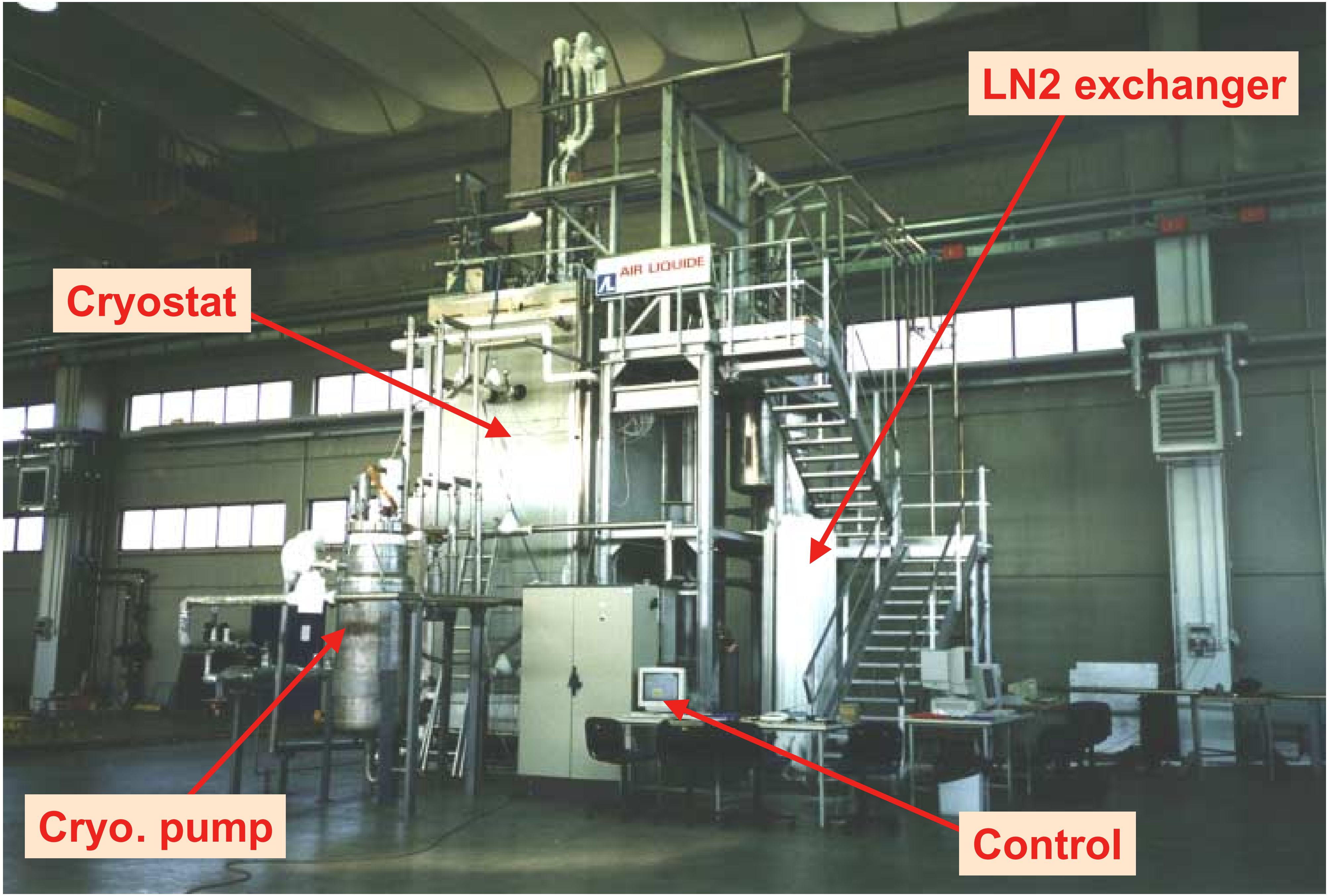
→ CAEN for readout electronics

ICARUS 15 ton (10m^3) prototype (1999-2000)

- A major step of the R&D program has been the construction and operation of a **10m^3 prototype**
  1. **Test of the cryostat technology**
  2. **Test of the "variable-geometry" wire chamber**
  3. **Test of the liquid phase purification system**
  4. **Test of trigger via scintillation light**
  5. **Large scale test of final readout electronics**

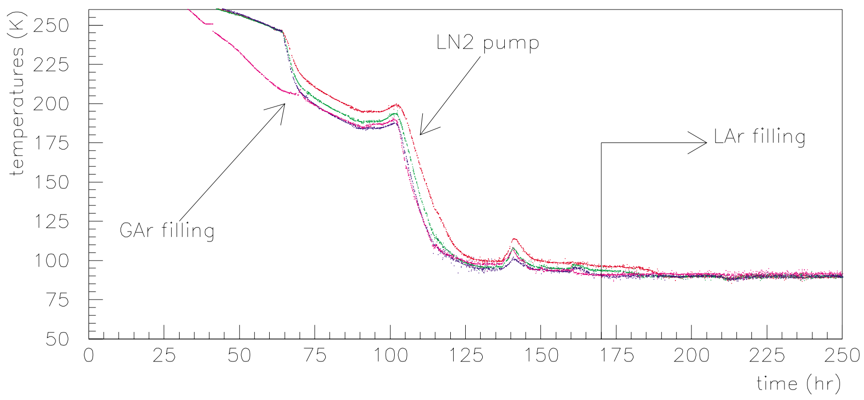
➜ *First operation of a 15 ton LAr mass as an actual "detector"*

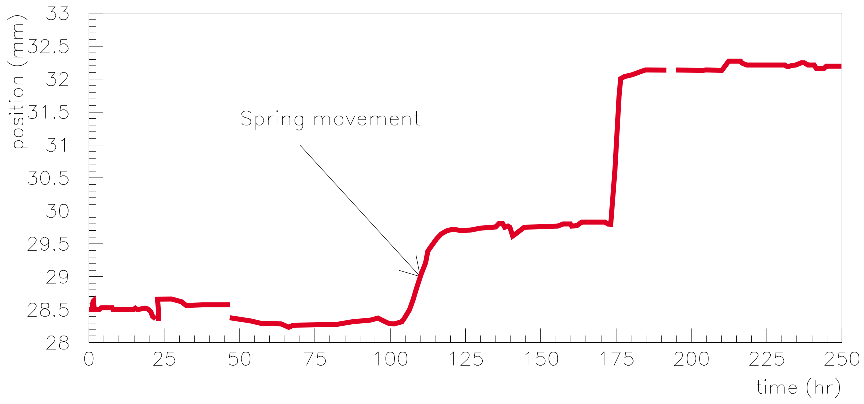
T15 installation @ LNGS (Hall di Montaggio)


LN2 exchanger
AIR LIQUIDE
Cryostat
Cryo. pump
Control

Cooling 15 ton prototype March '99

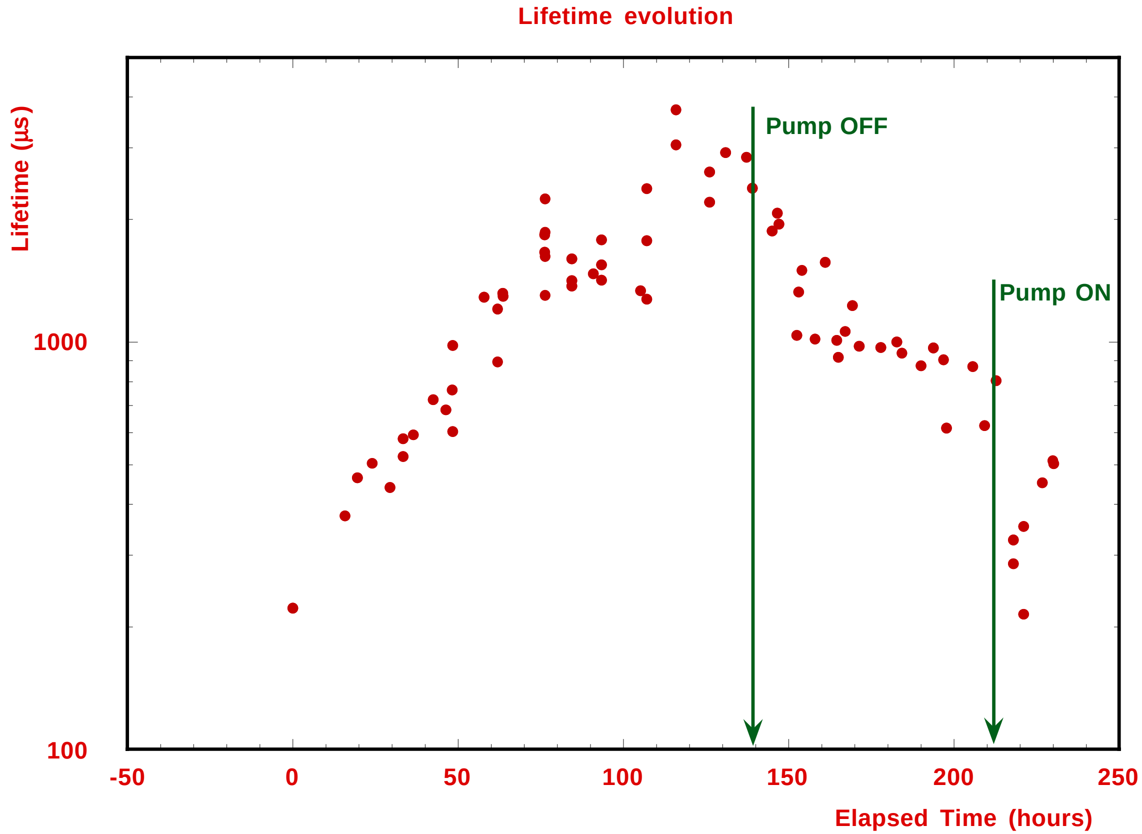
Temperature / Wire stretching





✖ Confirmation of the functionality of the *variable geometry* mechanics

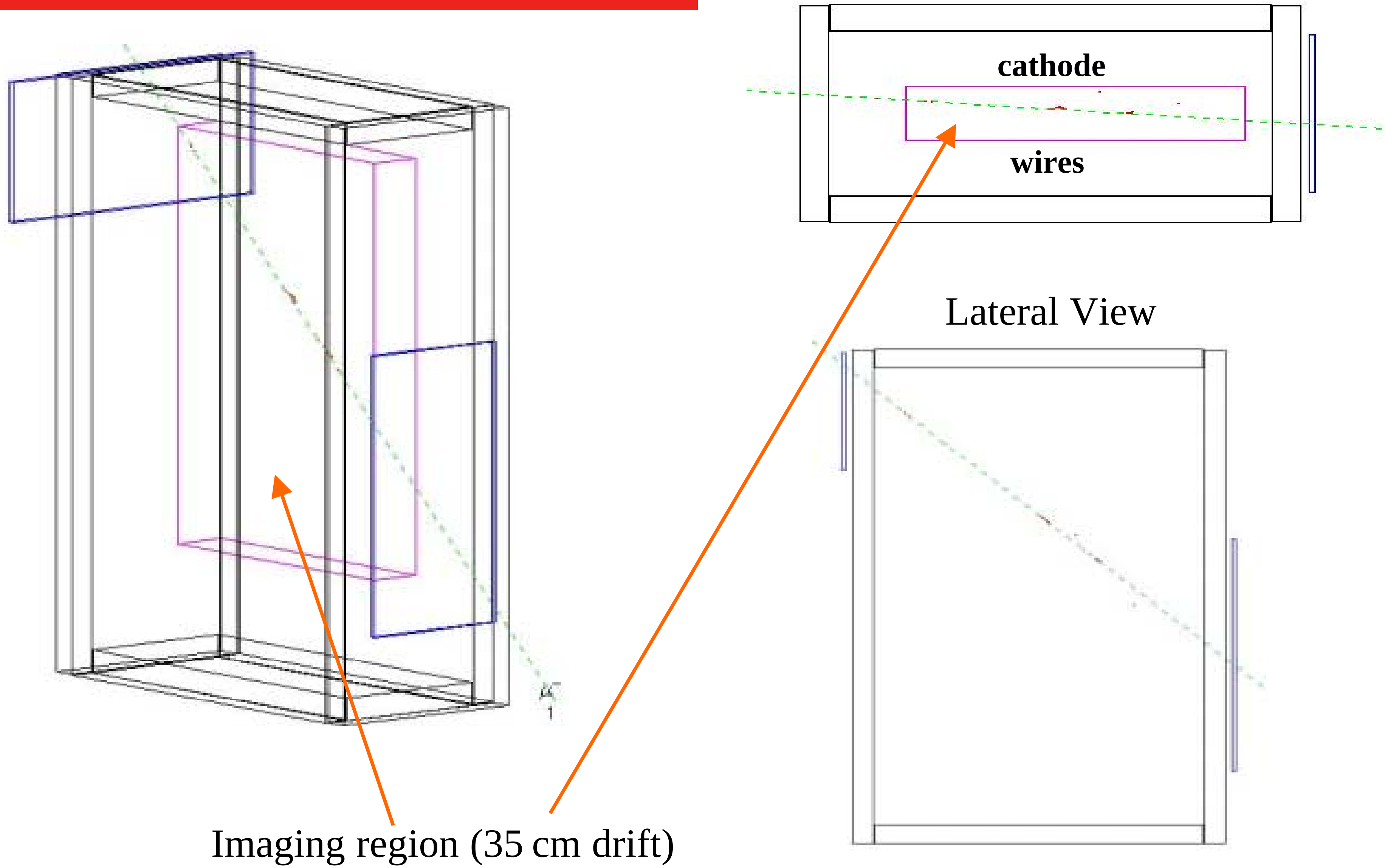
LAr purity



✖ **The electrons lifetime, after about 4 days of recirculation, was between 2 ms to 3 ms.**

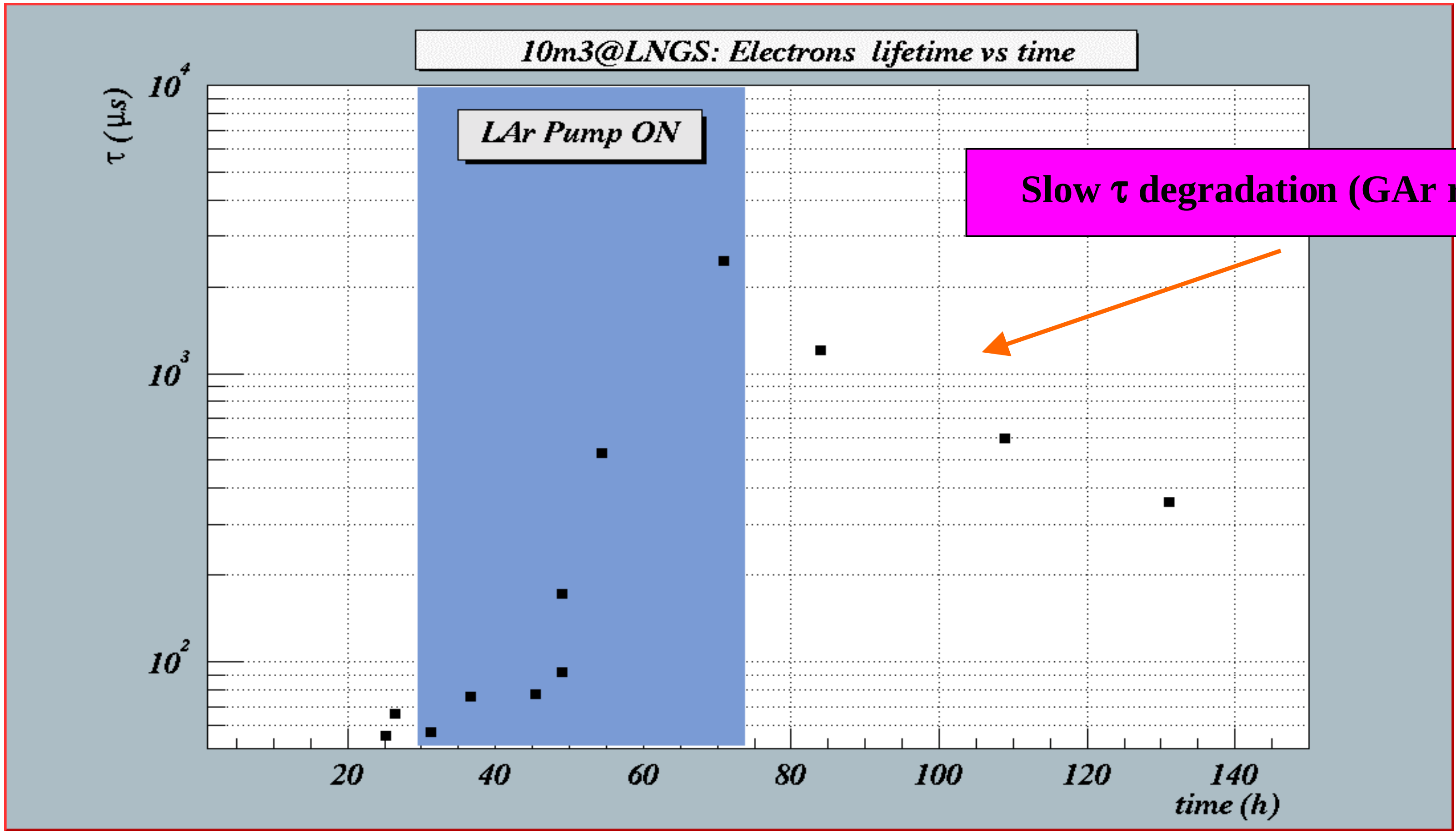
Internal Volumes Layout

Top View



Electron Lifetime Measurements

- Just after LAr filling: τ ~ 100μs, according to expectations based on residual leak rates (10^{-5} mbar/s).
- In a few days of LAr pump operation: τ > 2 ms

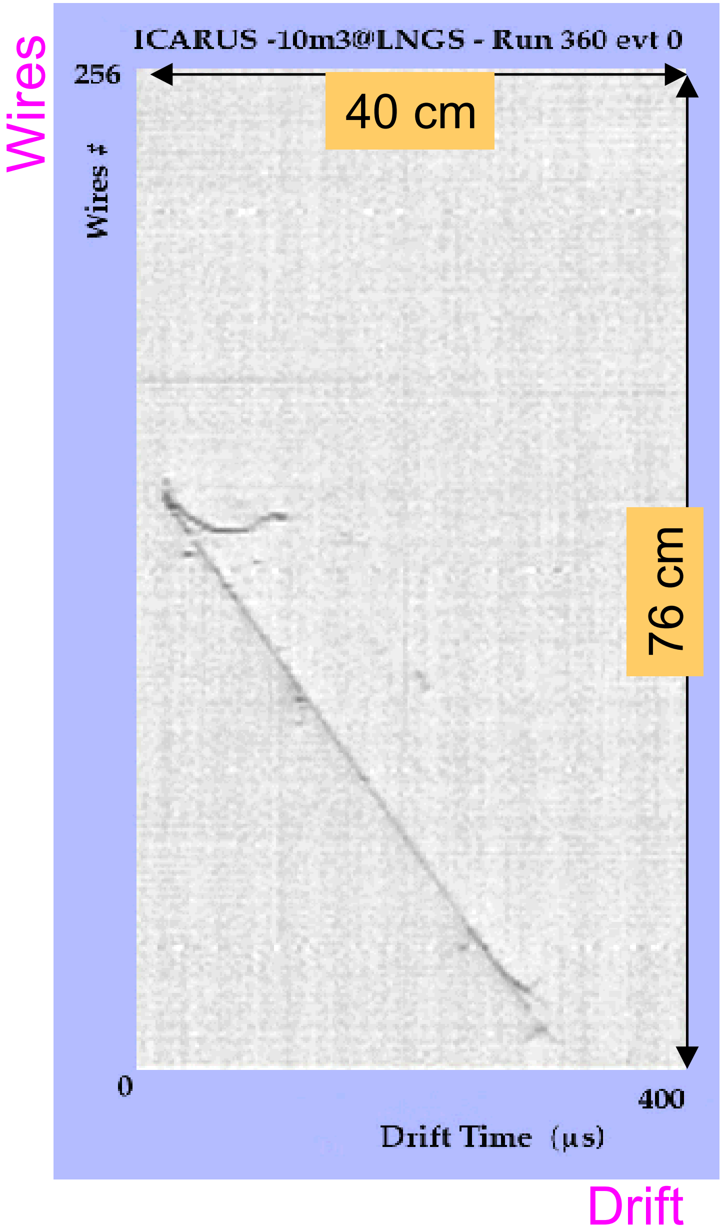


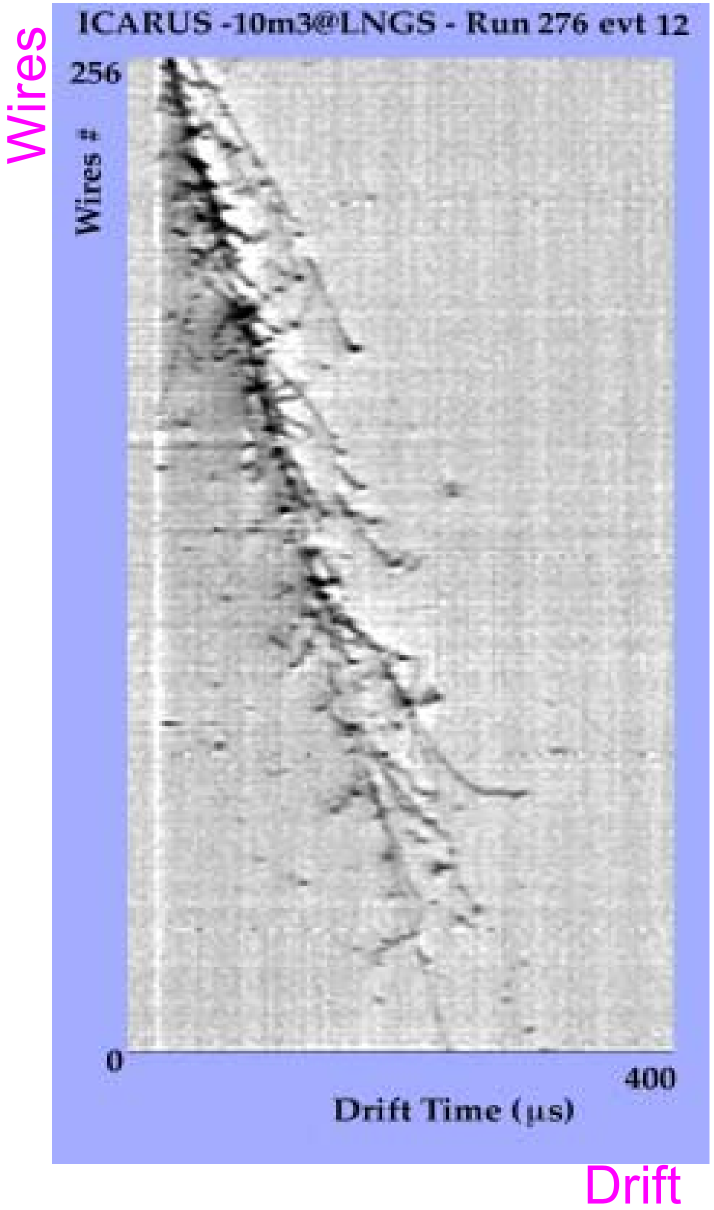
Slow τ degradation (GAr recirculation off)

Tracks in 15 ton prototype

10m^3 Module
at LNGS

Cosmic Ray tracks recorded during the 10 m^3 operation



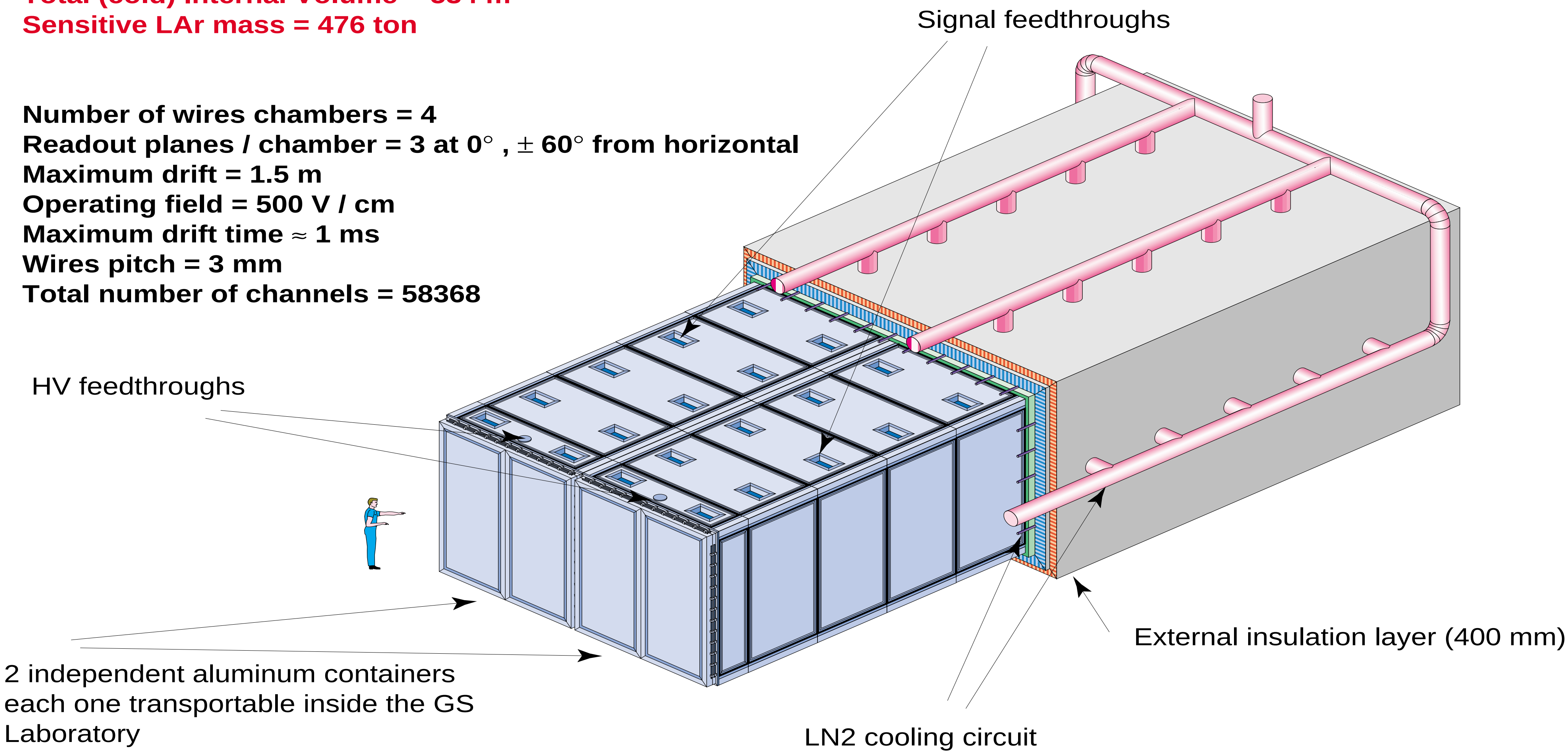


The ICARUS T600 module

Under construction

Number of independent containers = 2
Single container Internal Dimensions: Length = 19.6 m , Width = 3.9 m , Height = 4.2 m
Total (cold) Internal Volume = 534 m^3
Sensitive LAr mass = 476 ton

Number of wires chambers = 4
Readout planes / chamber = 3 at 0° , ± 60° from horizontal
Maximum drift = 1.5 m
Operating field = 500 V / cm
Maximum drift time ≈ 1 ms
Wires pitch = 3 mm
Total number of channels = 58368



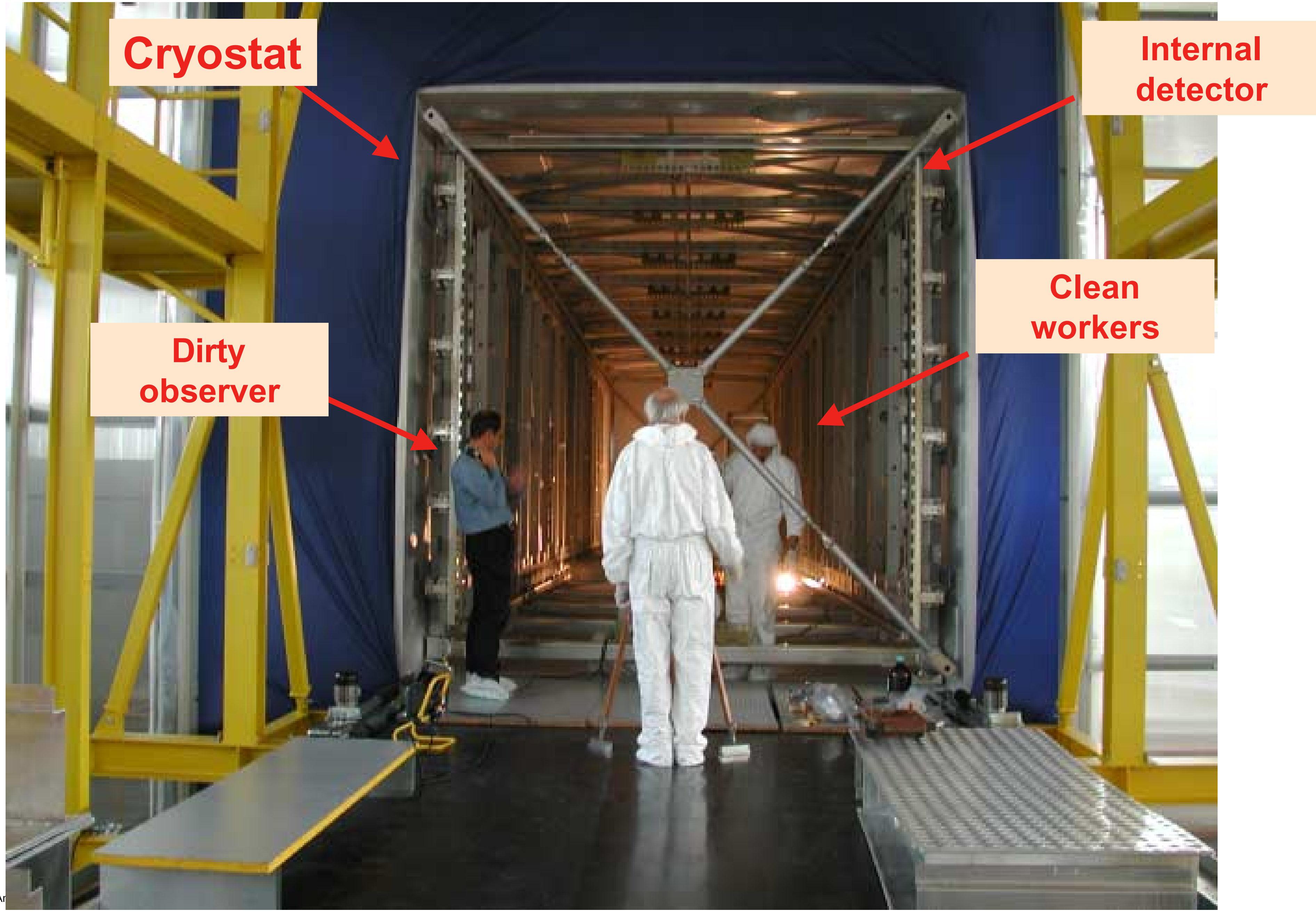
André Rubbia, ETH/Zürich, ICARUS Collaboration, 17/2/01

T600 assembly schedule

- Completed ***site preparation*** in Pavia for the T600 cryostat (**Nov 1999**)
  - → "clean room", "assembly island", floor, ...
- Delivery of the ***1st cryostat*** by AirLiquide (**Feb 2000**)
  - → Successful vacuum tightness and mechanical stress tests
- Beginning of ***assembly of the internal detector mechanics*** (**Mar 2000**)
- Completion of assembly and positioning of inner detector frames (**Jul 2000**)
- Installation of ***30000 wires*** + ***signal cables*** (**Jul 2000-Oct 2000**)
- Delivery of the ***2nd cryostat*** of AirLiquide (**Aug 2000**)
  - → Successful vacuum tightness and mechanical stress tests
- Installation of ***scintillation light*** and all ***slow control devices*** (**Jul 2000-Dec 2000**)
- ***H.V. and field electrodes system*** installation (**Oct 2000- Jan 2001**)
- Installation of the ***48 electronic racks*** on top of dewar (**Dec 2000-ongoing**)
- Installation of ***external heat insulation*** (for both dewars) and ***LAr and LN_2 cryogenic circuits*** (**Dec 2000-Jan 2001**)
- Semi-module now ready to be sealed.

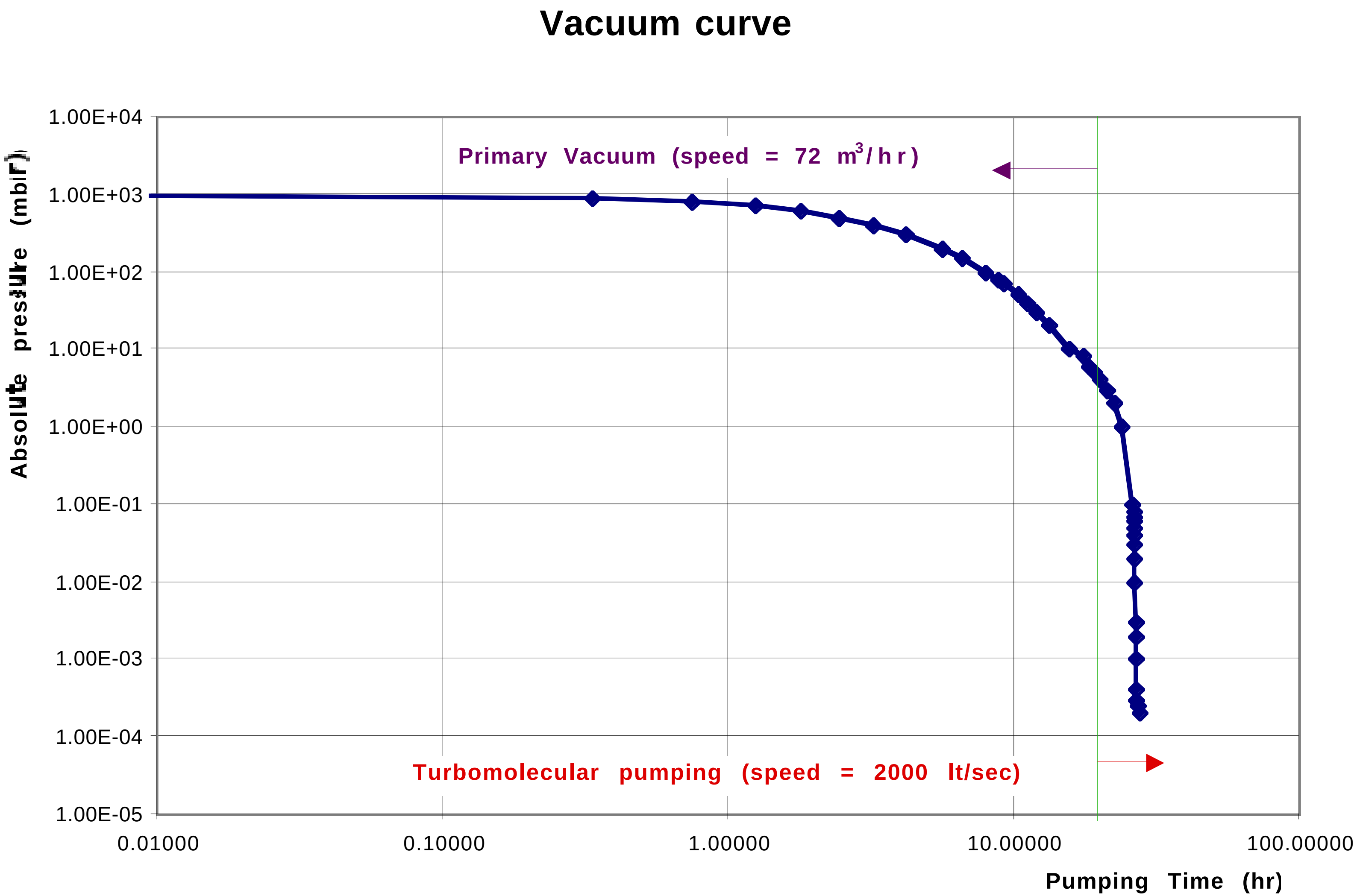
First half-module delivery in Pavia (Feb 29, 2000)

Assembly of the T600 internal detector (Mar-Jul 2000)

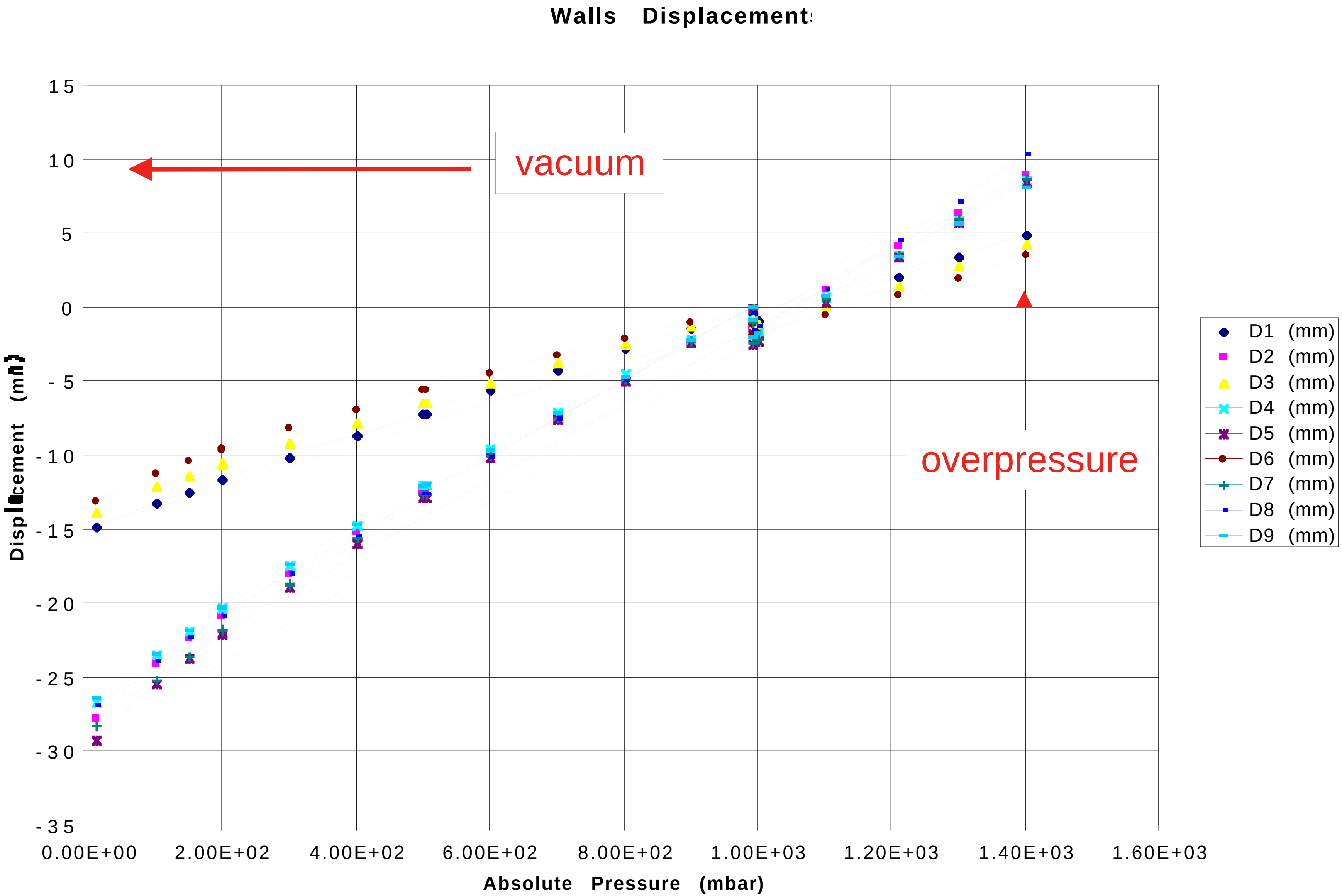


Second half-module during the vacuum test (Jul 2000)

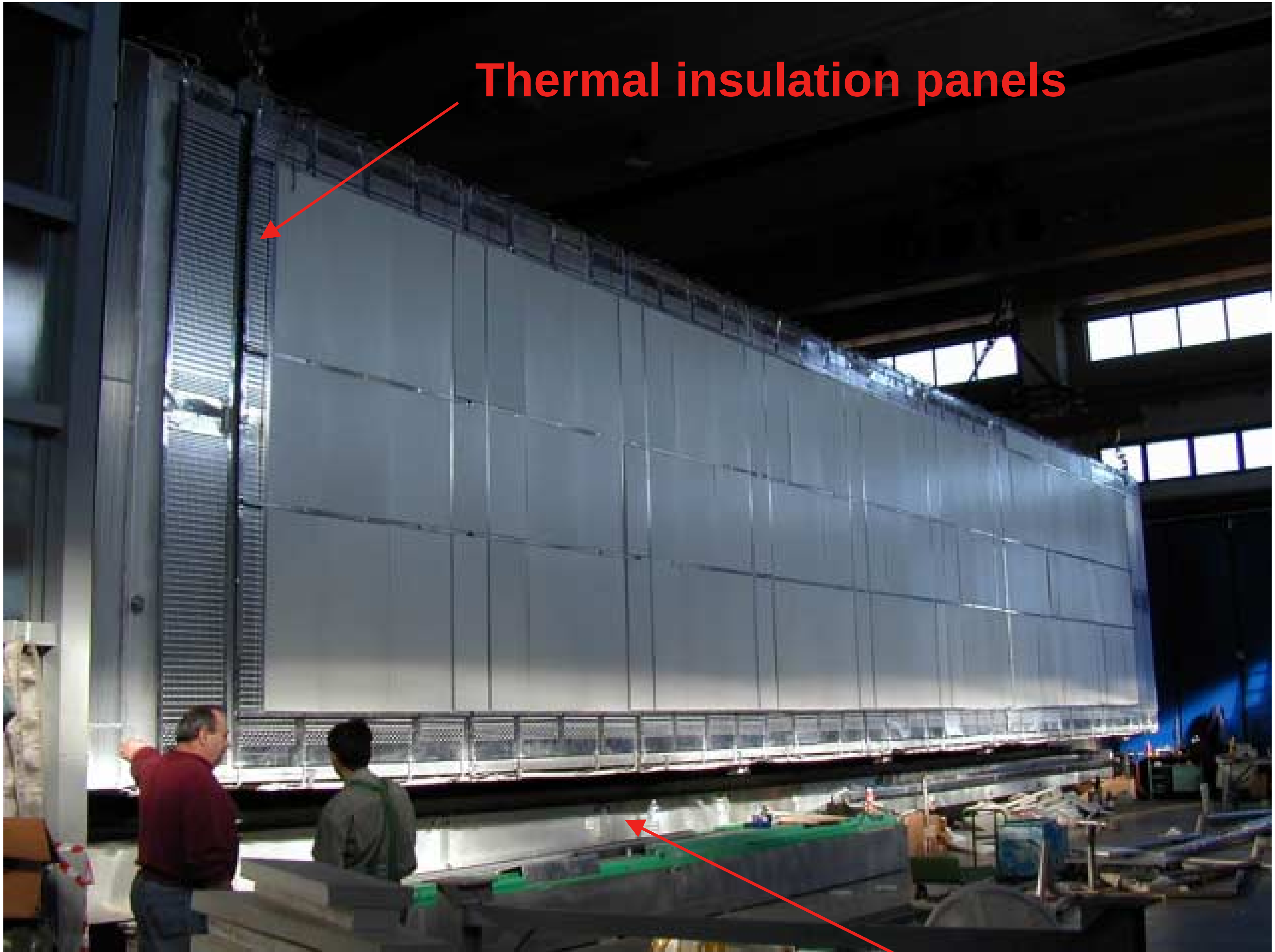
Vacuum Tests - Second half-module

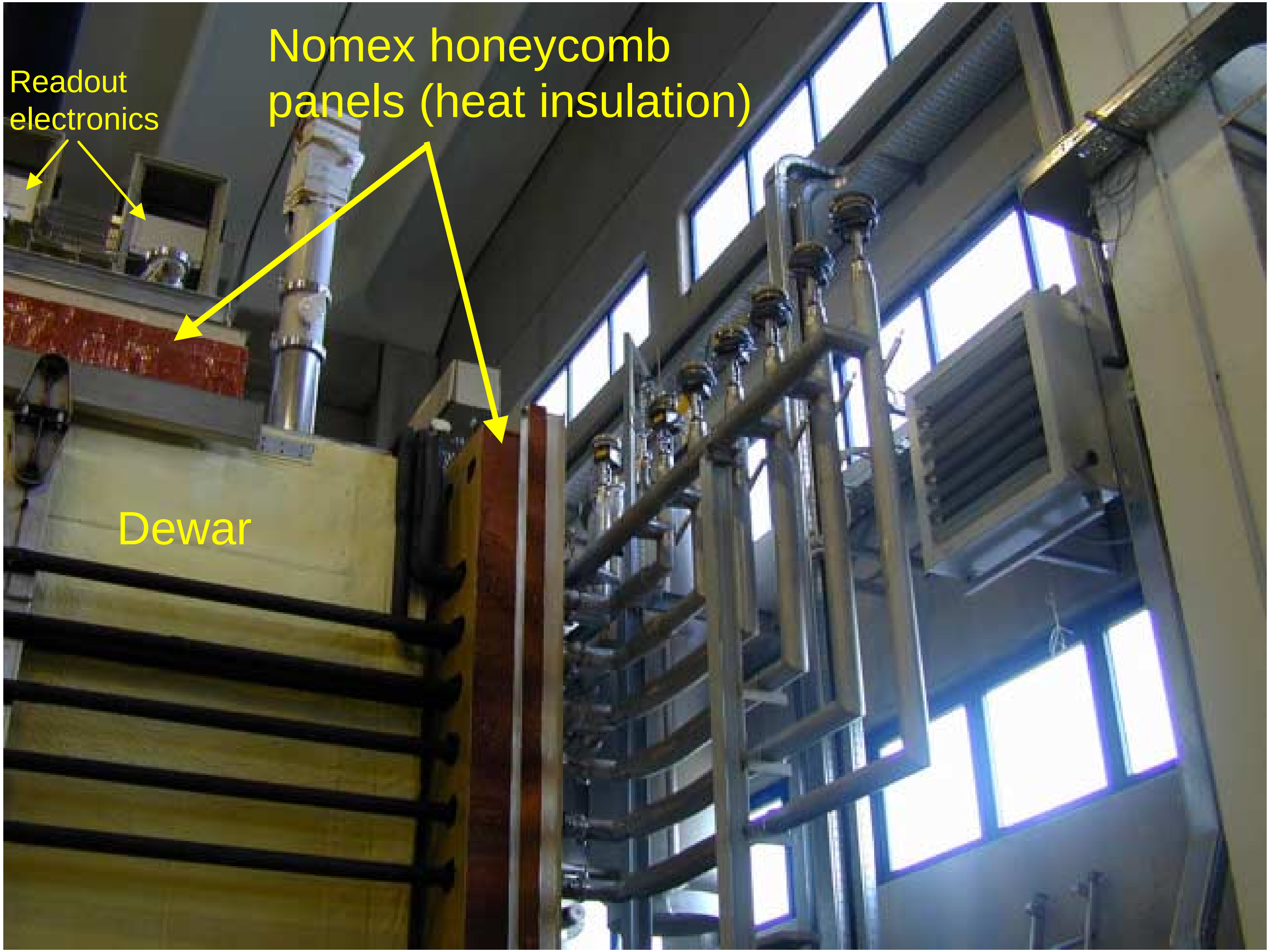


Dewar behaviour under inner pressure change



Second half-module (delivered Aug 2000)



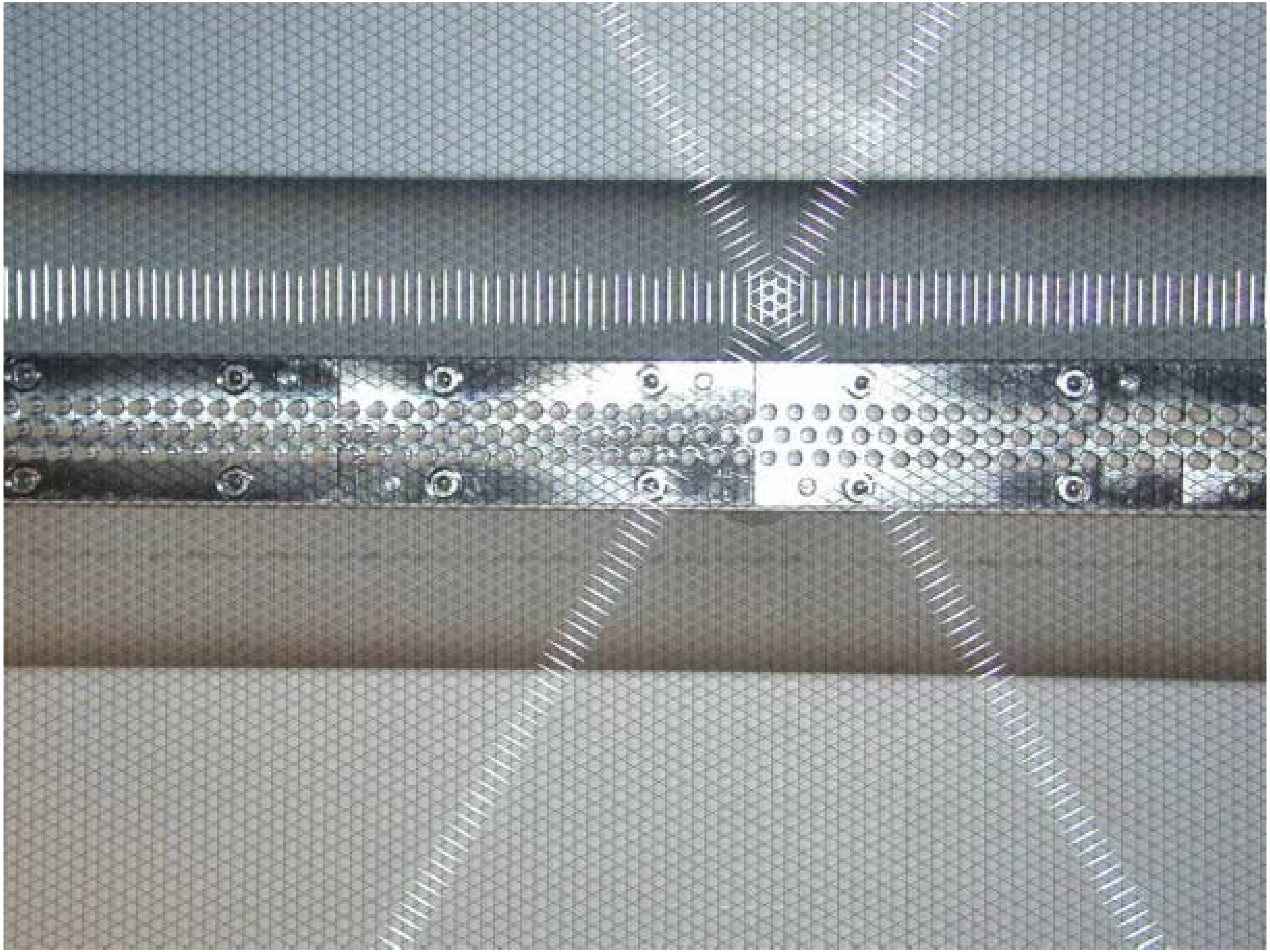

Readout electronics
Nomex honeycomb panels (heat insulation)
Dewar

Installation slow control devices (Jul 2000)

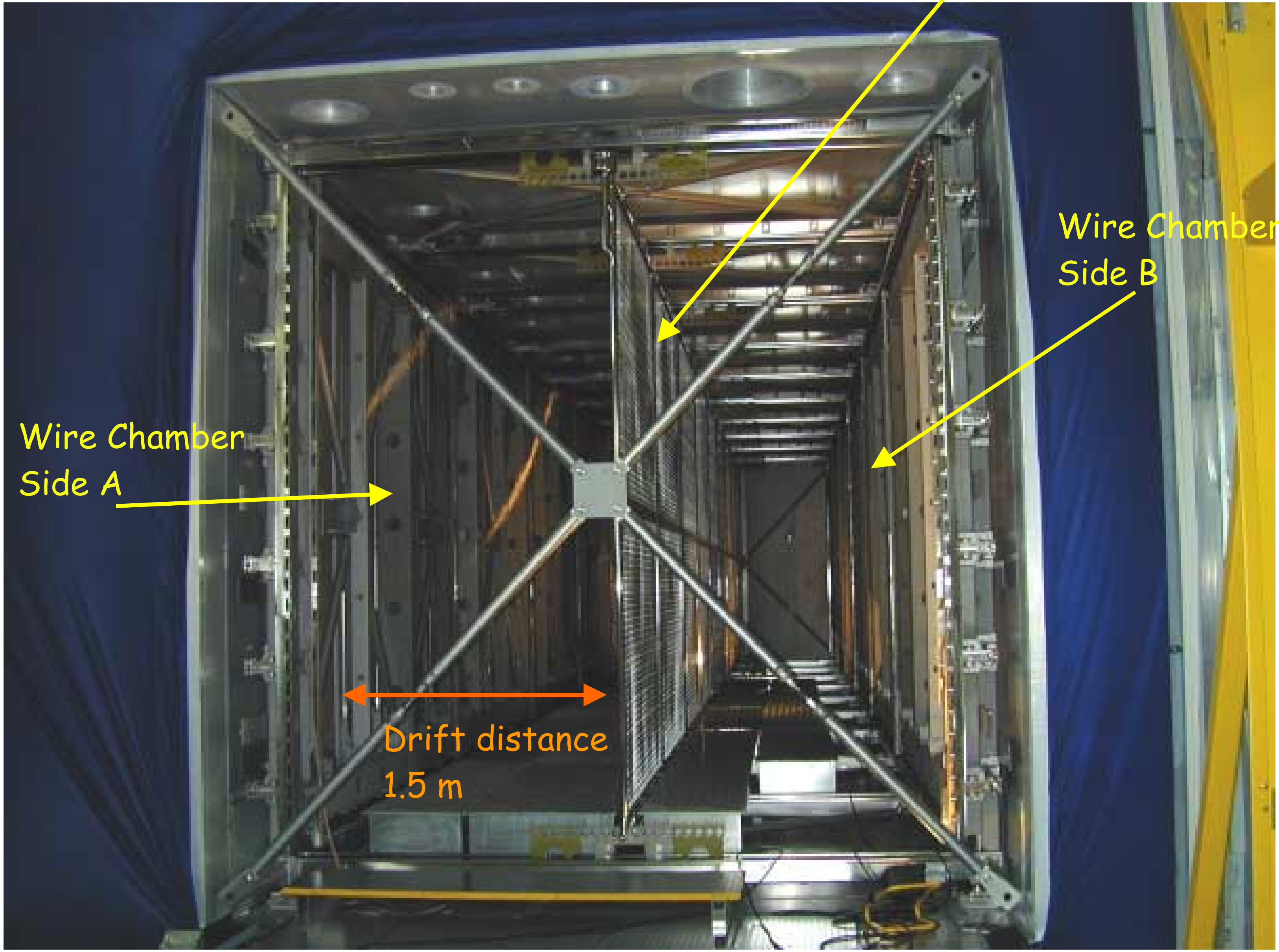
Wire installation in T600 internal detector (Jul-Oct 2000)

The three wire planes at 0°,±60° (wire pitch = 3mm)

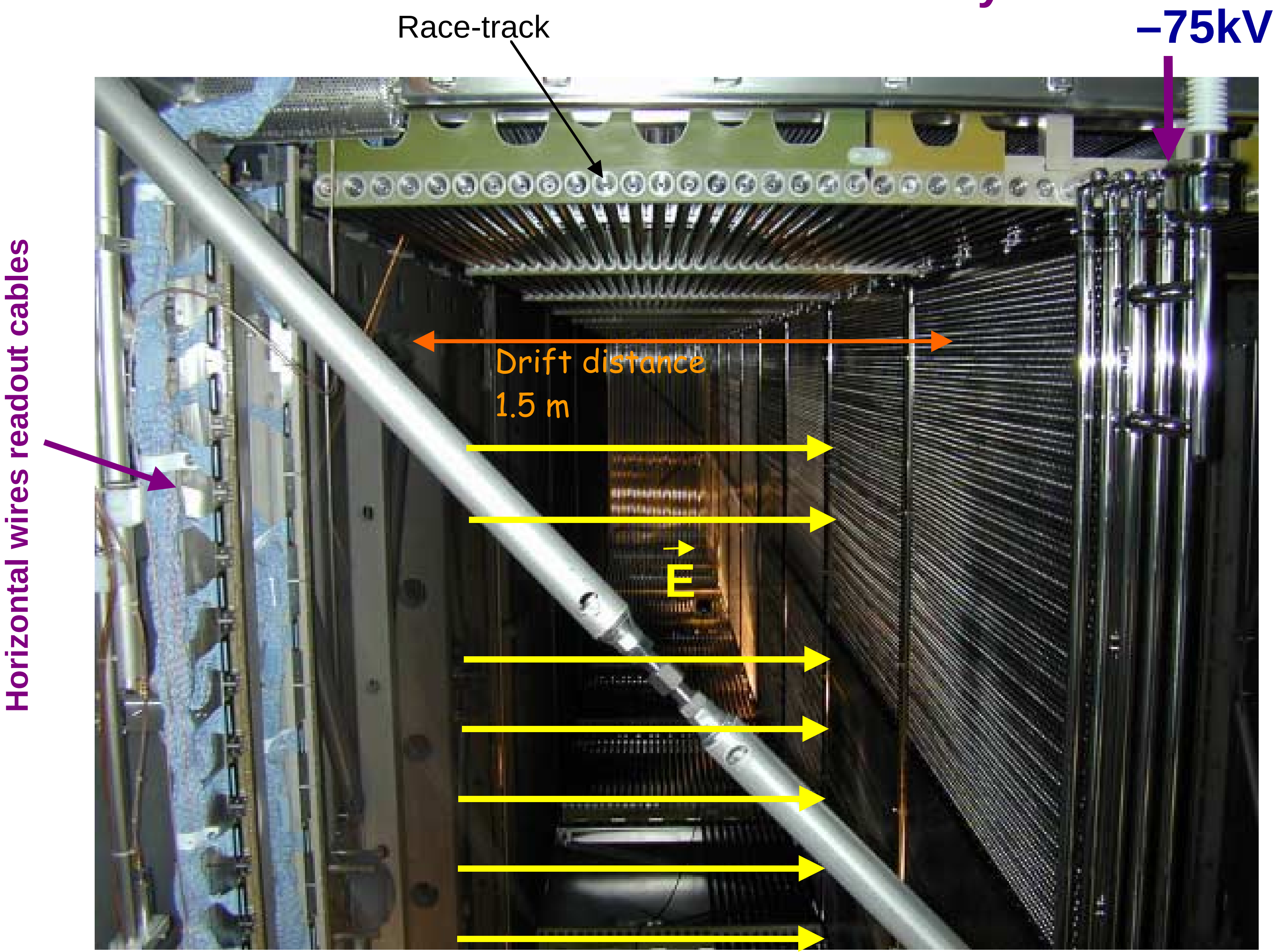
Wires crossing the spacers (wire pitch = 3mm)



T600 - Completed Internal Detector view



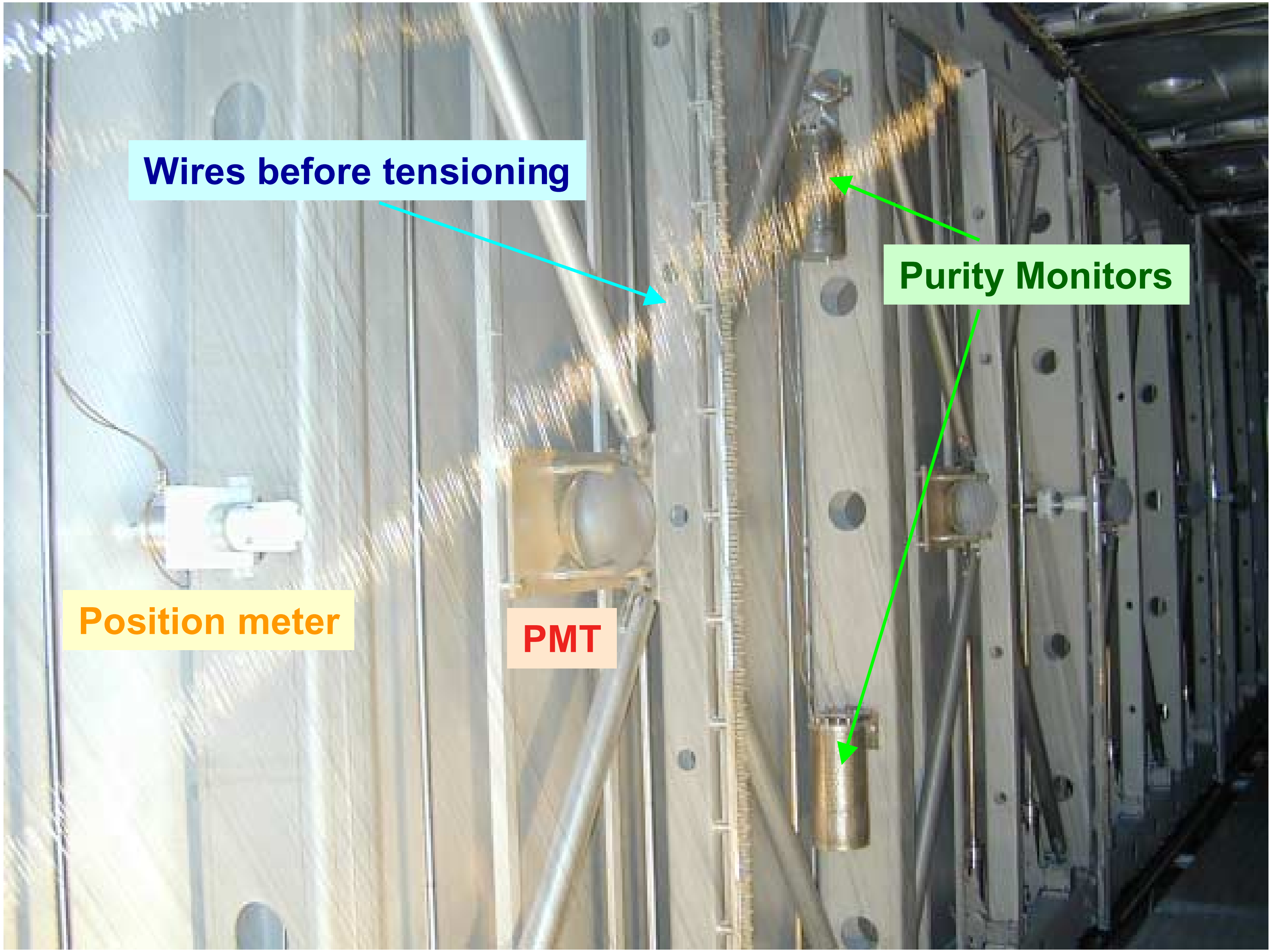
Drift H.V. and field electrodes system



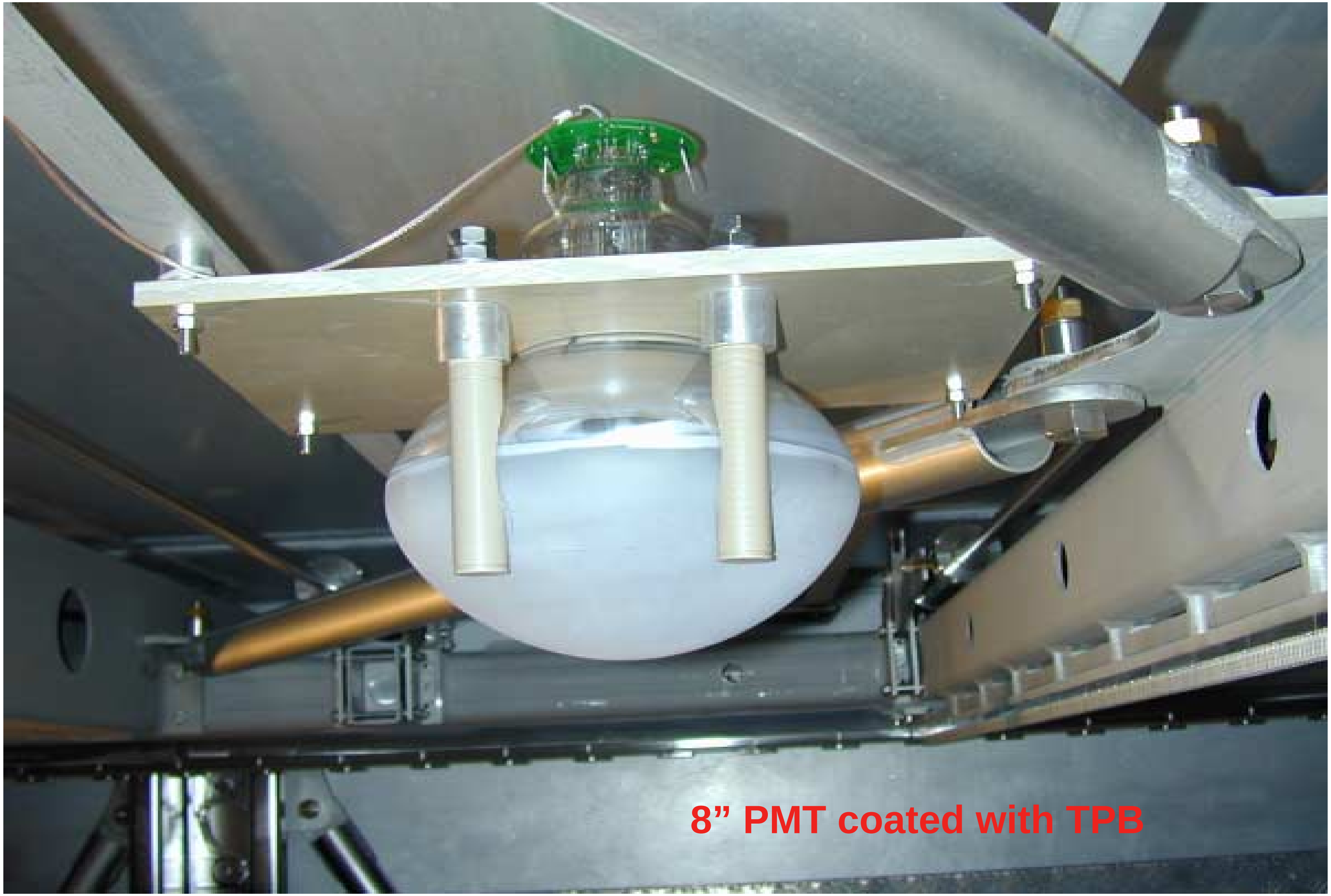
Slow control system and scintillation light detection

- Several **instrumentation**, most of it custom designed to work at LAr temperature in high purity environment, has been built tested and installed:
  - → LAr Purity monitors
  - → High precision LAr level meters
  - → Position meters for the wires tensioning springs and for the container walls
  - → Temperature probes
- **Detection of LAr scintillation light** (VUV λ=128 nm, attenuation length in LAr $\approx$90cm, $1\div2\times10^4$ γ per MeV deposited)
  - → Provide **help for triggering** and **T_0 measurement**.
  - → Bare PMT's immersed in LAr with wavelength shifter deposited on the glass window
    - – Test and qualification of PMT at LAr temperature:8 inches EMI PMTs with special treated bialkali photocathode to work at cryogenic temperature.
    - – Choice of most efficient wavelength shifter (**TPB** = TetraPhenylButadiene), deposition method (spray), aging properties, pollution of LAr, etc.

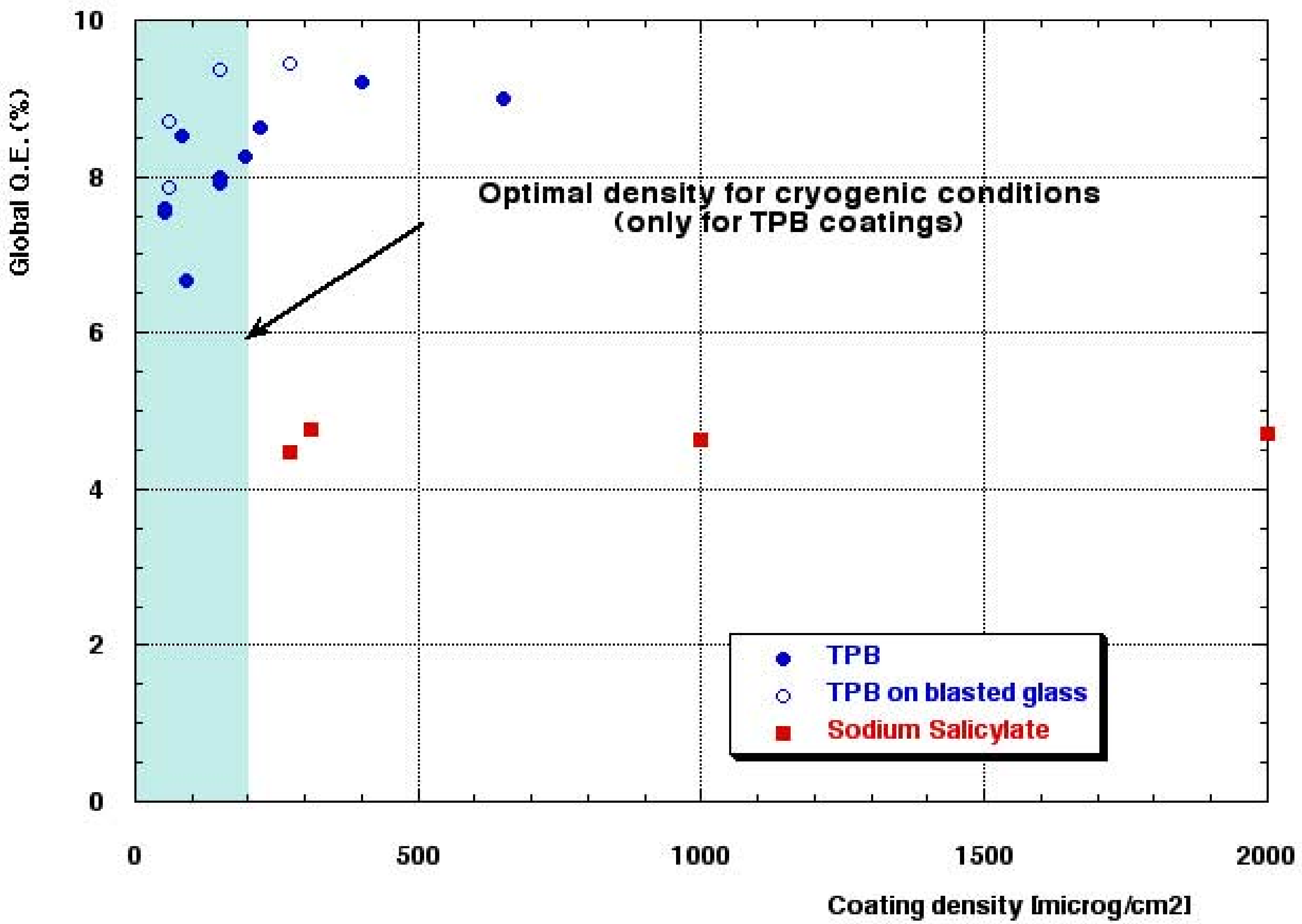
Slow control sensor (behind wire planes)



Scintillation light collection
(in total 20 PMTs on detector walls)



Global Quantum Efficiency
(PMT + wavength-shifter coating)



Readout electronic installation on top of dewar (Dec 2000-now)

Electronic rack

chimneys

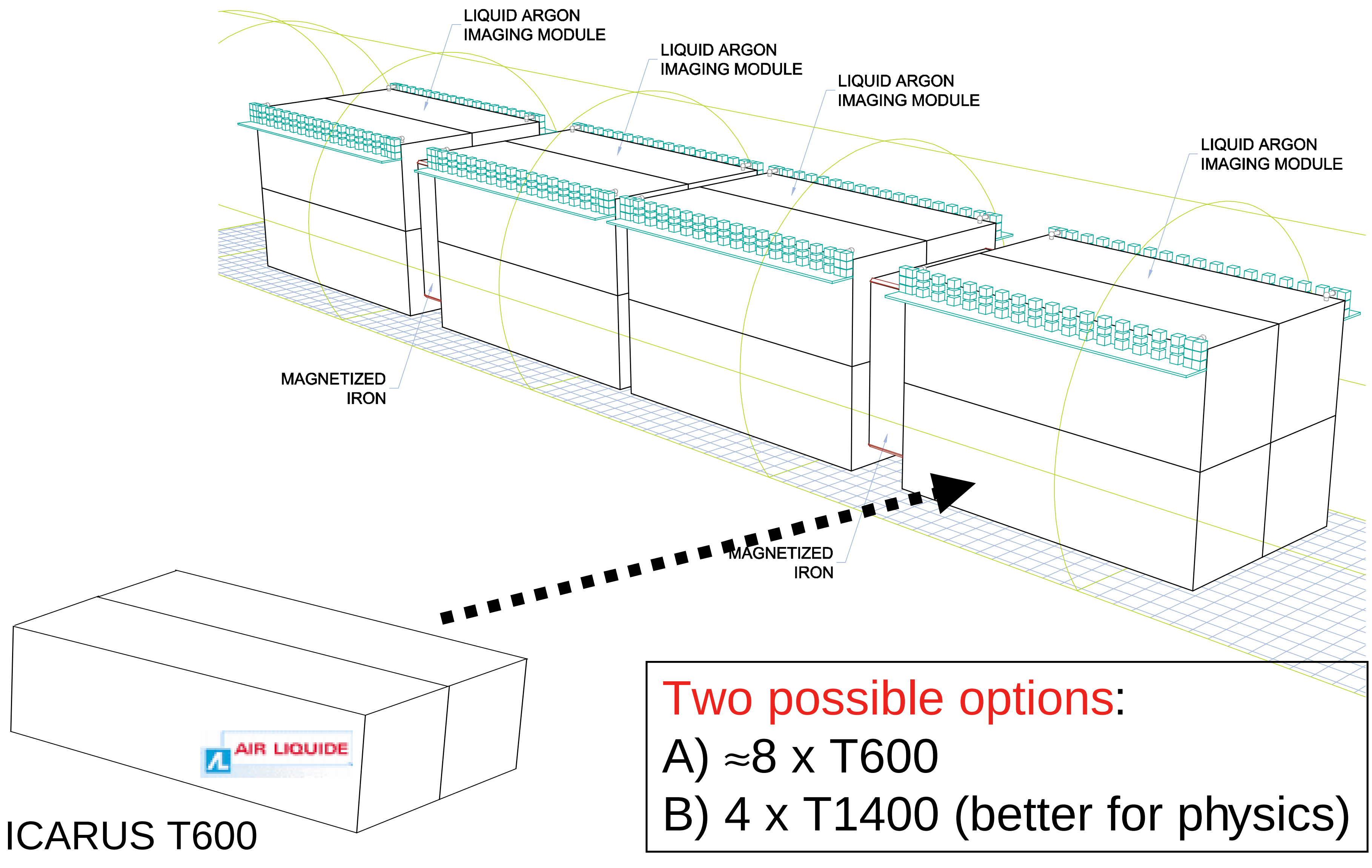
Readout electronic installation on top of dewar (Dec 2000-now)

Man-hole (after sealing, the only way to get inside!)

Perspectives of ICARUS

- The ICARUS T600 detector
  - ➜ has a **physics program** of its own, immediately relevant for neutrino oscillation physics: **solar+SN neutrinos, atmospheric neutrinos**
  - ➜ Though with limited statistics, due its relatively small mass, compared to the standard for underground detectors set by the operating SuperKamiokande.
- However, the T600 should also be considered as one more step towards larger detector masses.
  - ➜ solving technical issues associated with actual operation of a large mass LAr device in an underground site (LNGS Tunnel).
  - ➜ fully establish the imaging, PID, calorimetric energy reconstruction capabilities of REAL events, during steady detector operations
  - ➜ In situ proof of actual physics performance of this novel detector technique, in particular measurement of backgrounds, extrapolable to larger mass detectors
- Physics issues for both present and future LAr detectors:
  - Atmospheric ν
  - Solar+SN ν
  - CNGS+Nufactory ν
  - **p** decay

Proposed setup ICARUS 5kt in LNGS Hall B



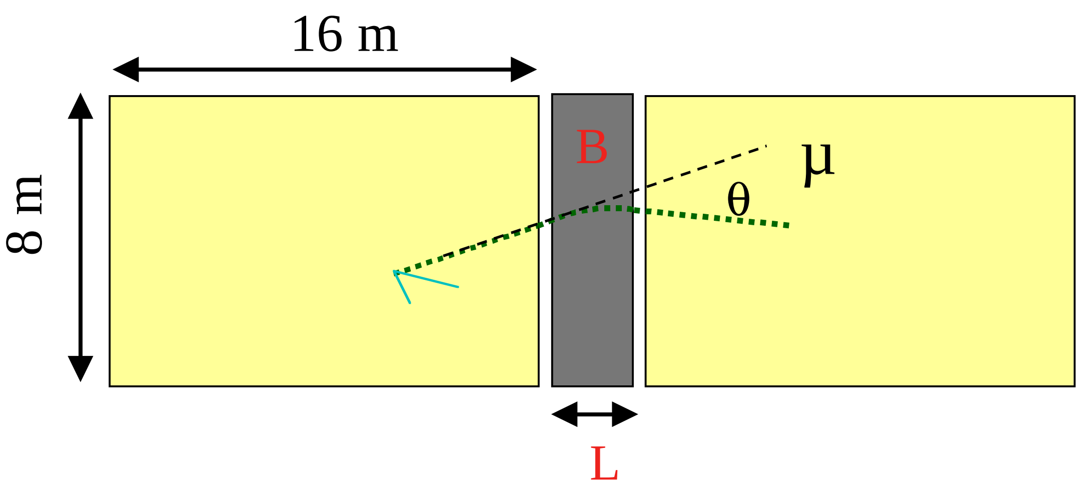
Two possible options:

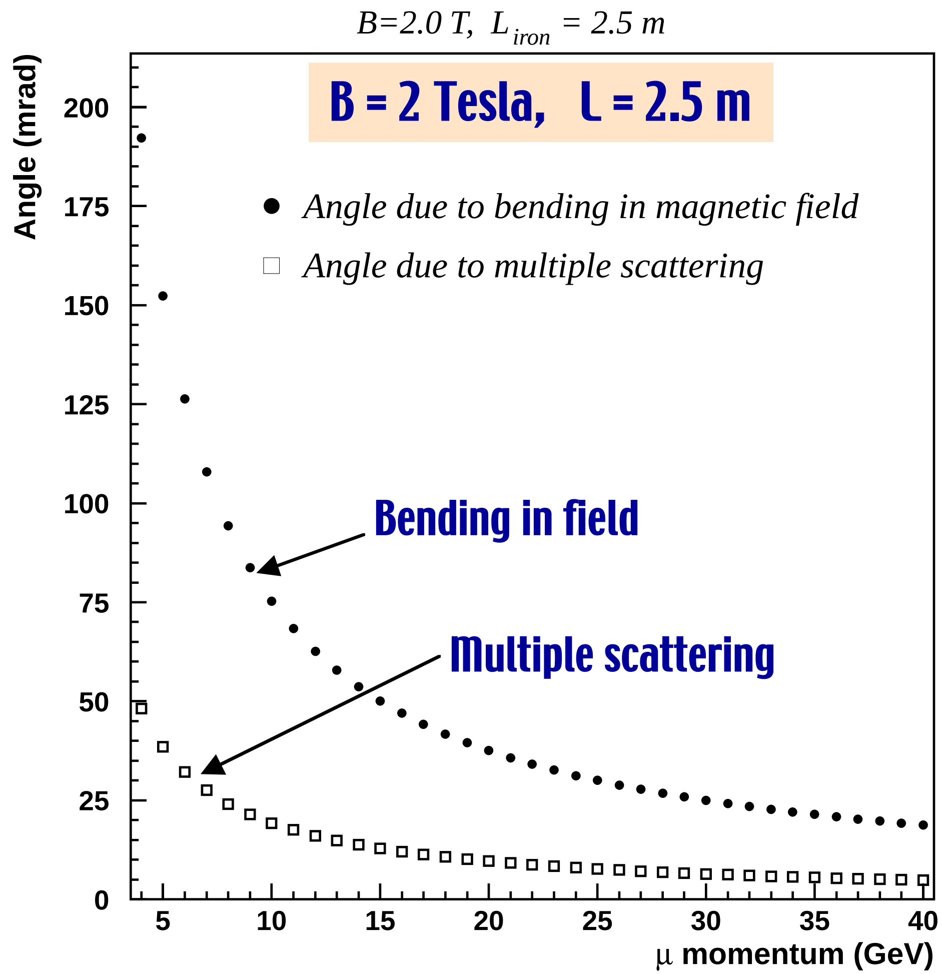
A) ≈8 x T600

B) 4 x T1400 (better for physics)

Muon bending measurement

- We consider a design in which the muon escaping the liquid Argon is bent by a magnetized piece of iron



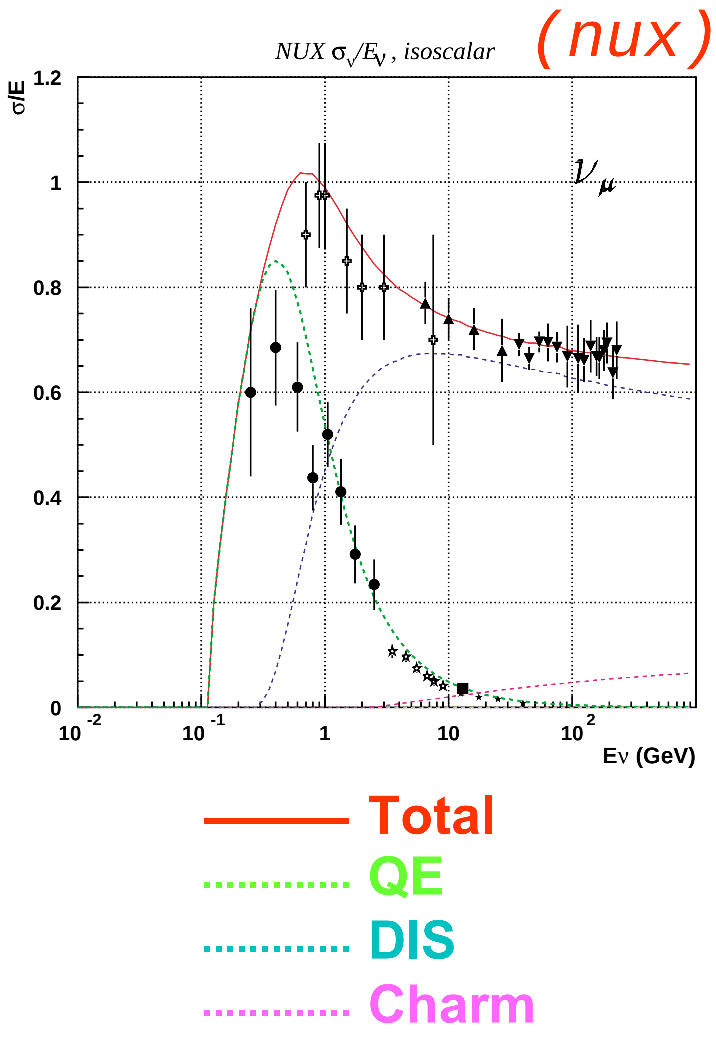


The bending angle θ is measured with the tracks observed in two subsequent liquid argon module

$\Delta p/p \approx 25\%$

Charge confusion: $\sim 10^{-4}$

Atmospheric neutrino rates (5 kt x year)



	No osci	Δm^2_{23} (eV^2) 5×10^{-4}	1×10^{-3}	3.5×10^{-3}	5×10^{-3}
Muon-like	675 ± 26	515 ± 23	495 ± 22	470 ± 22	455 ± 21
Contained	418 ± 20	319 ± 18	307 ± 18	291 ± 17	282 ± 17
Partially-Contained	257 ± 16	196 ± 14	188 ± 14	179 ± 13	173 ± 13
No proton	260 ± 16	190 ± 14	185 ± 14	170 ± 13	165 ± 13
One proton	205 ± 14	160 ± 13	150 ± 12	145 ± 12	140 ± 12
Multi-prong	210 ± 14	165 ± 13	160 ± 13	155 ± 12	150 ± 12
$P_{lepton} < 400$ MeV	285 ± 17	205 ± 14	200 ± 14	185 ± 14	175 ± 13
$P_{lepton} \geq 400$ MeV	390 ± 20	310 ± 18	295 ± 17	285 ± 17	280 ± 17
Electron-like	380 ± 19	380 ± 19	380 ± 19	380 ± 19	380 ± 19
No proton	160 ± 13	160 ± 13	160 ± 13	160 ± 13	160 ± 13
One proton	120 ± 11	120 ± 11	120 ± 11	120 ± 11	120 ± 11
Multi-prong	100 ± 10	100 ± 10	100 ± 10	100 ± 10	100 ± 10
$P_{lepton} < 400$ MeV	185 ± 14	185 ± 14	185 ± 14	185 ± 14	185 ± 14
$P_{lepton} \geq 400$ MeV	195 ± 14	195 ± 14	195 ± 14	195 ± 14	195 ± 14
NC	480 ± 22	480 ± 22	480 ± 22	480 ± 22	480 ± 22
TOTAL	1535 ± 39				

Events/year

Nuclear effects
fully embedded in *FLUKA* nuclear model

CNGS events in 5 kton, 4 years running

$\theta_{23} = 45°, \theta_{13} = 7°$

		20 kton×year (4 years running)		
		Δm^2_{23} (eV^2)		
	No osci	1×10^{-3}	3.5×10^{-3}	5×10^{-3}
ν_μ CC	54300	53820	49330	44910
$\bar{\nu}_\mu$ CC	1090	1088	1070	1057
ν_e CC	437	437	437	436
$\bar{\nu}_e$ CC	29	29	29	29
ν NC		17550		
$\bar{\nu}$ NC		410		
$\nu_\mu \to \nu_e$ CC	-	7	74	143
$\nu_\mu \to \nu_\tau$ CC	-	52	620	1250
$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	-	< 1	< 1	1
$\bar{\nu}_\mu \to \bar{\nu}_\tau$ CC	-	< 1	6	13

$\nu_\mu \to \nu_\tau$ oscillations (I)

- Analysis of the electron sample
  - Exploit the small intrinsic ν_e contamination of the beam (0.8% of ν_μ CC)
  - Exploit the unique e/π^0 separation

$$\nu_\mu \to \nu_\tau$$

$$\nu_\tau + N \to \tau + jet; \quad \tau \to e\nu\nu$$

Charged current (CC)

$Br \approx 18\%$

$$\Delta m^2 = 3.5 \times 10^{-3} eV^2 \quad \Rightarrow \quad 110 \;\; events$$

Background:

$$\nu_e + N \to e + jet$$

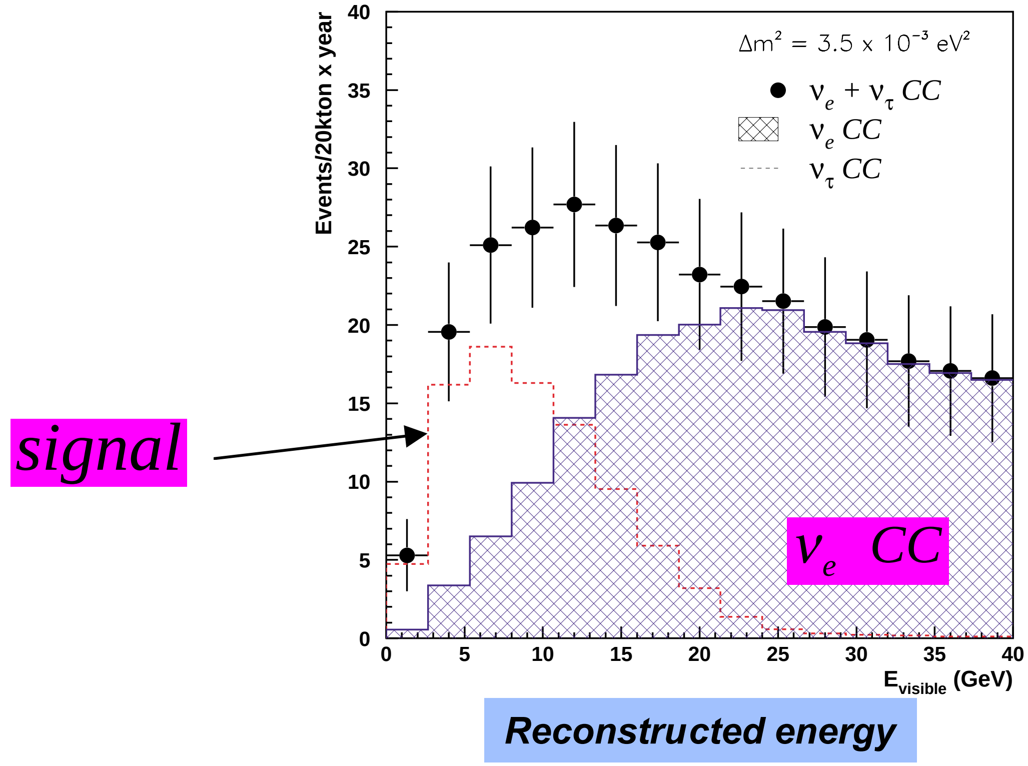
Charged current (CC)

$$470 \;\; \nu_e CC$$

Statistical excess visible before cuts ⇒ this is the main reason for performing this experiment at long baseline !

$\nu_\mu \rightarrow \nu_\tau$ oscillations (II)

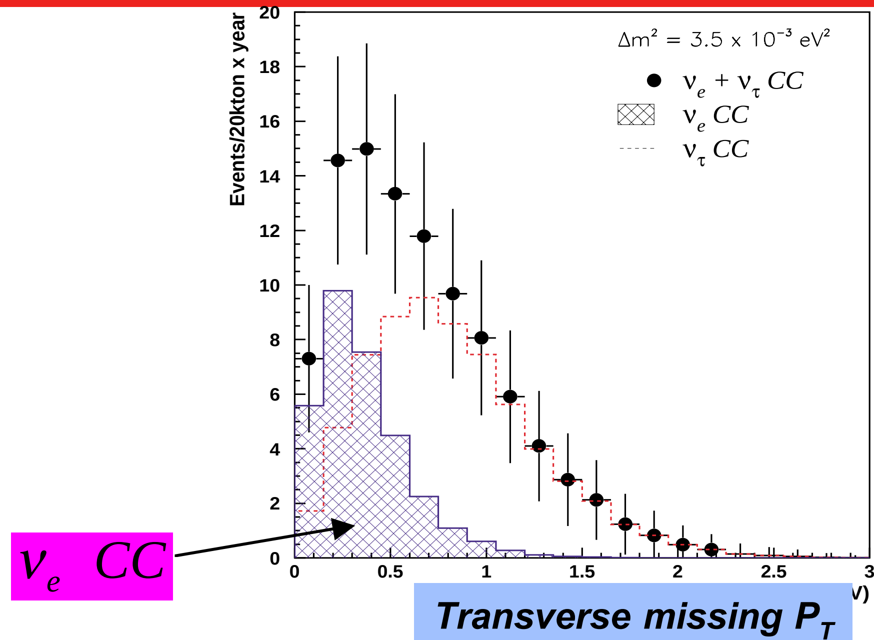
- Reconstructed visible energy spectrum of electron events clearly evidences excess from oscillations into tau neutrino



Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 10^{-2}$ eV^2
Initial	100	437	29	9.3	71	111	779
Fiducial volume	88	383	25	8.2	64	97	686
One candidate with momentum > 1 GeV	72	365	25	6.7	50	80	561
$E_{vis} < 18$ GeV	67	64	5	6.2	46	75	522

$\nu_\mu \rightarrow \nu_\tau$ oscillations (III)

- Kinematical selection in order to enhance S/B ratio
- Can be tuned "a posteriori" depending on the actual Δm^2
- For example, with cuts listed below, reduction of background by factor 100 for a signal efficiency 33%



Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 10^{-2}$ eV^2
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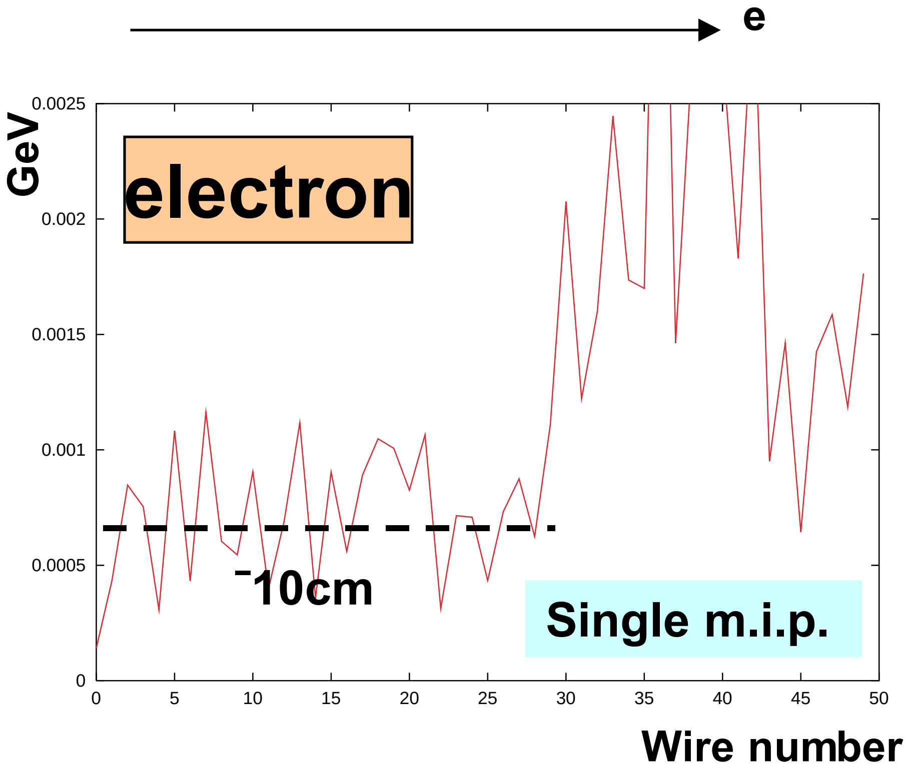
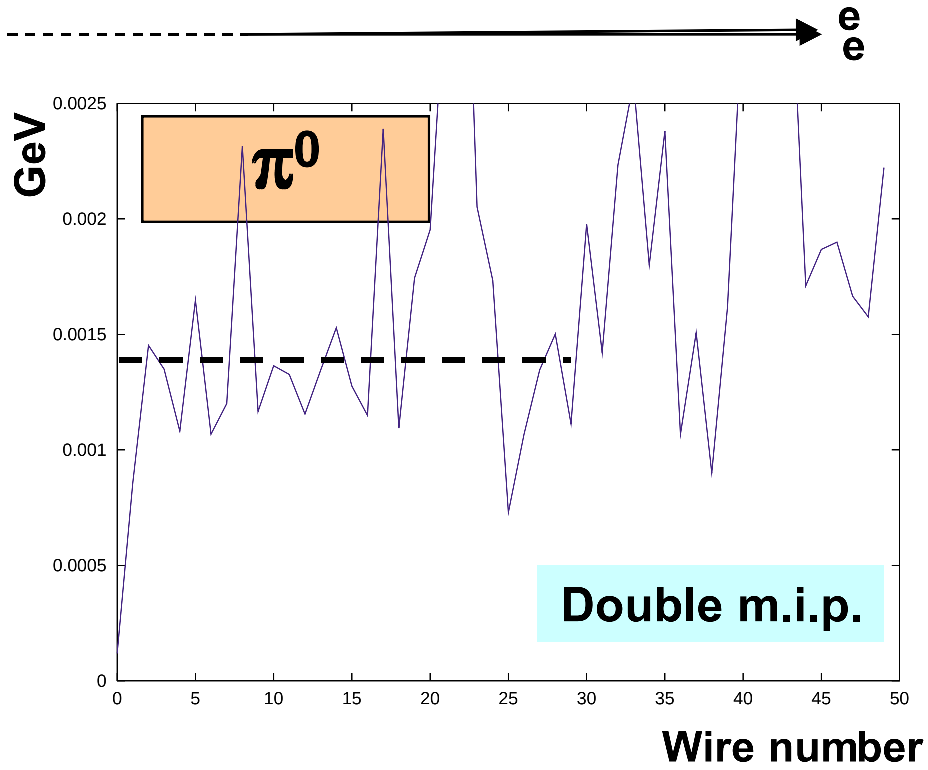
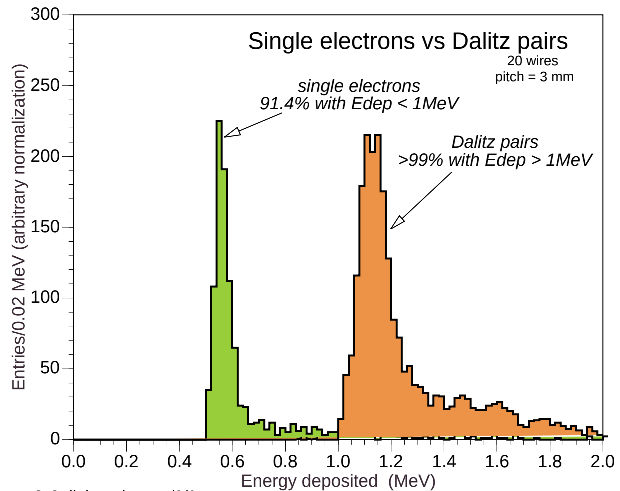
$E_{vis} < 18$ GeV	67	64	5	6.2	46	75	522
$P_T^e < 0.9$ GeV	54	31	3	5.0	38	60	421
$P_T^{lep} > 0.3$ GeV	51	29	2	4.7	35	56	397
$P_T^{miss} > 0.6$ GeV	33	4	0.4	3.1	23	37	257

e/π^0 discrimination





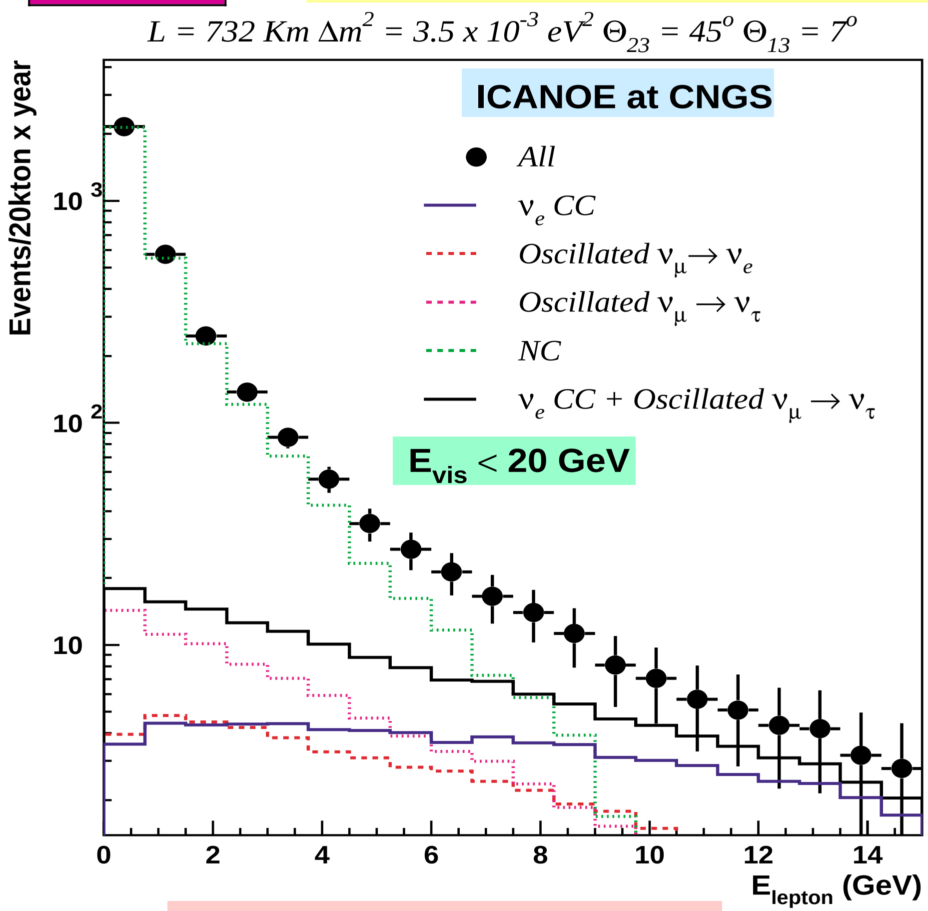
Wire pitch = 3 mm ¯ 0.02 X_0



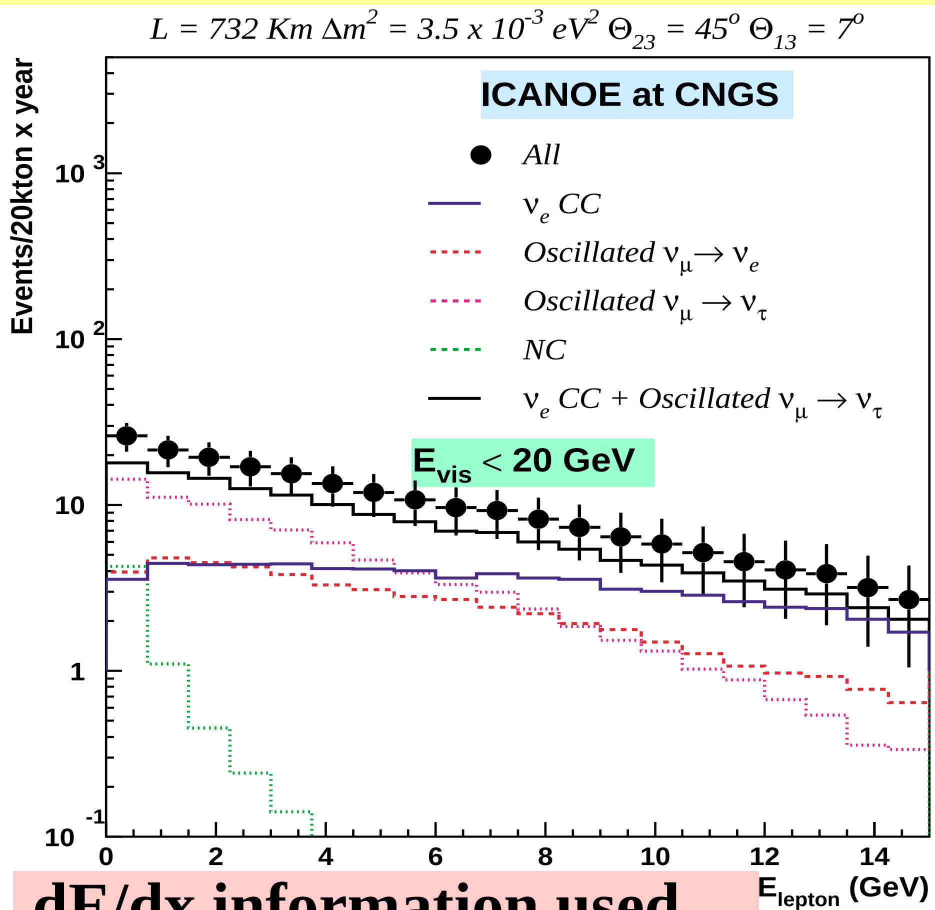
Combined rejection: dE/dx + photon converted within 3 cm of vertex: > 500

ν_e CC versus ν NC discrimination (I)

NC → γ converting within 3 cm (10 samples) from primary vertex considered as electron candidate



NO dE/dx information used

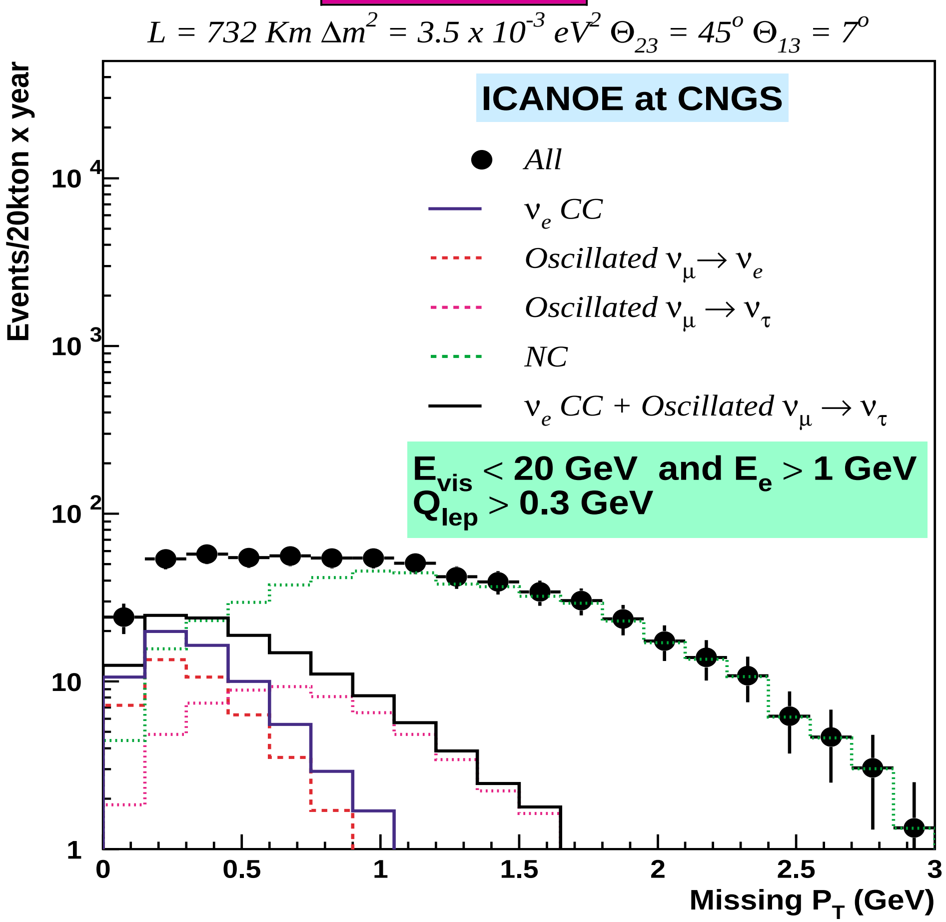


dE/dx information used

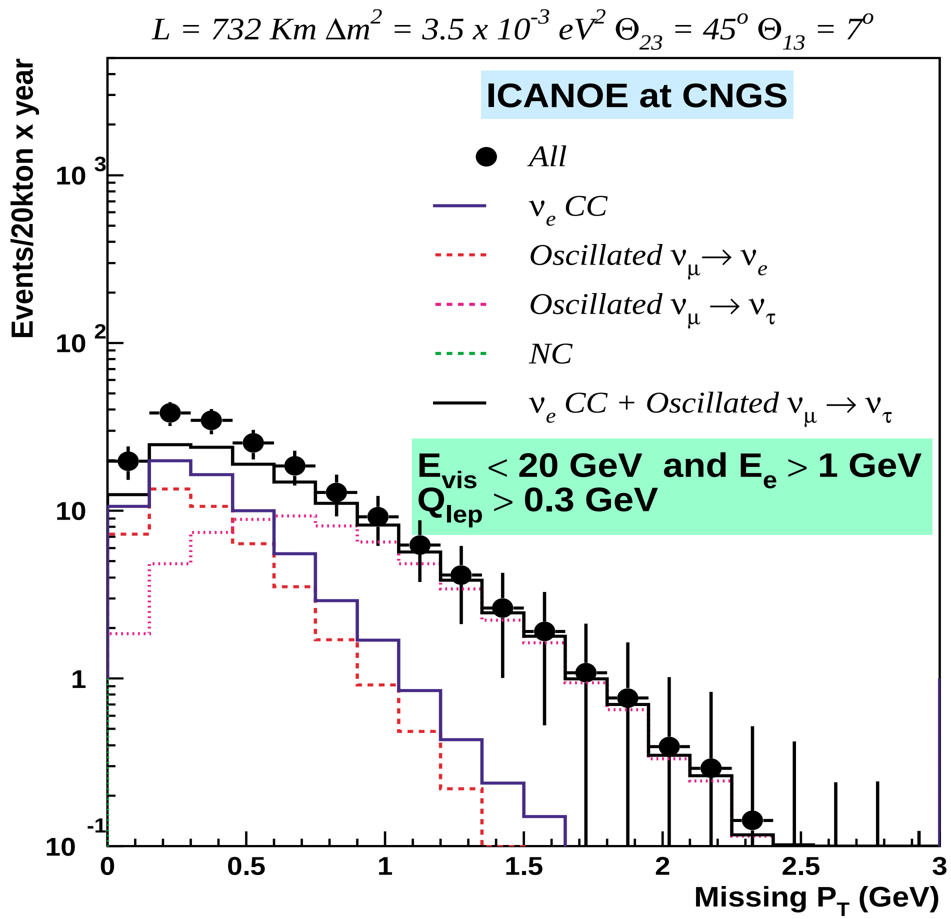
Single vs double m.i.p. algorithm provides **>500 rejection factor**

ν_e CC versus ν NC discrimination (II)

NC rejection → Additional discrimination power provided by event kinematics



NO dE/dx information used



dE/dx information used

Search for $\theta_{13} \neq 0$

ICANOE
4 years

Δm^2_{32}=3.5x10^{-3} eV^2; $\sin^2 2\theta_{23} = 1$

Cuts: Fiducial, $E_e > 1$ GeV, $E_{vis} < 20$ GeV

$\Delta m^2_{23} = 3.5 \times 10^{-3}$ eV^2, $\theta_{23} = 45^o$

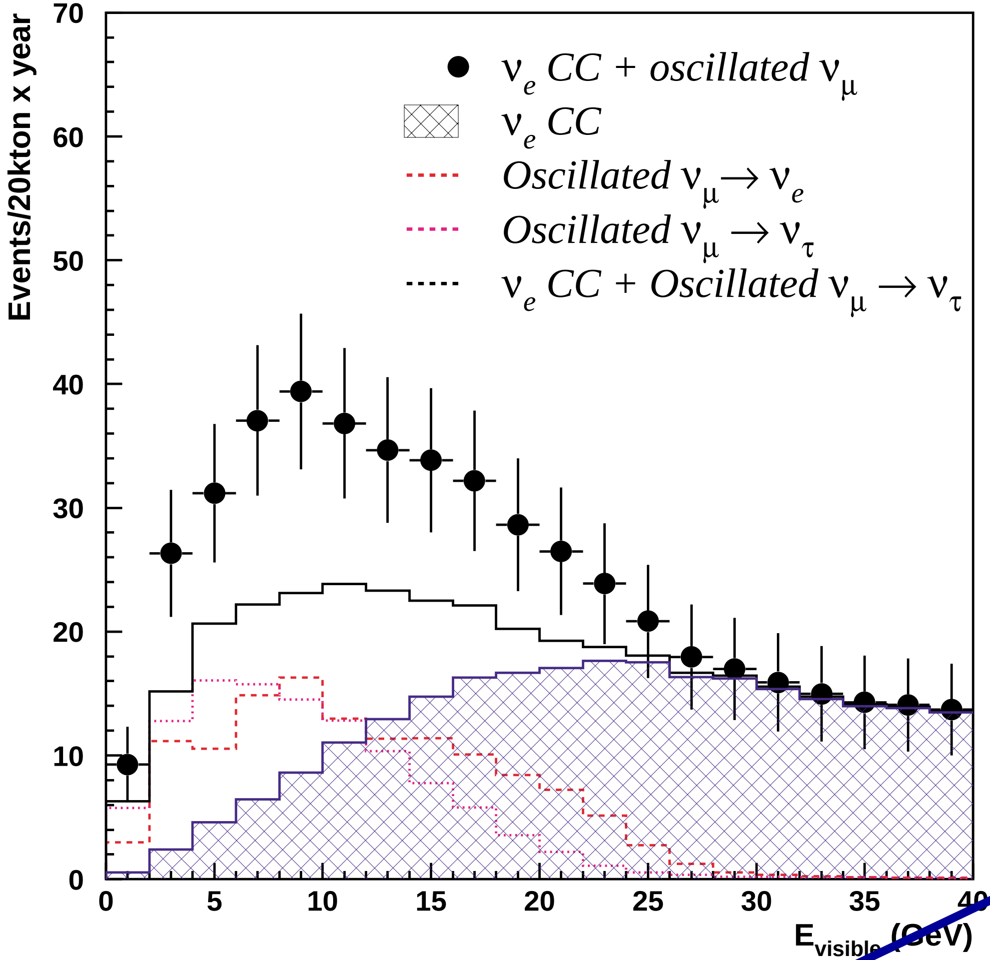
θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu \to \nu_\tau$ $\tau \to e$	$\nu_\mu \to \nu_e$	Total	Statistical significance
9	0.095	79	74	84	237	6.8σ
8	0.076	79	75	67	221	5.4σ
7	0.058	79	76	51	206	4.1σ
5	0.030	79	77	26	182	2.1σ
3	0.011	79	77	10	166	0.8σ

$$P(\nu_\mu \to \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \Delta^2{}_{32}$$

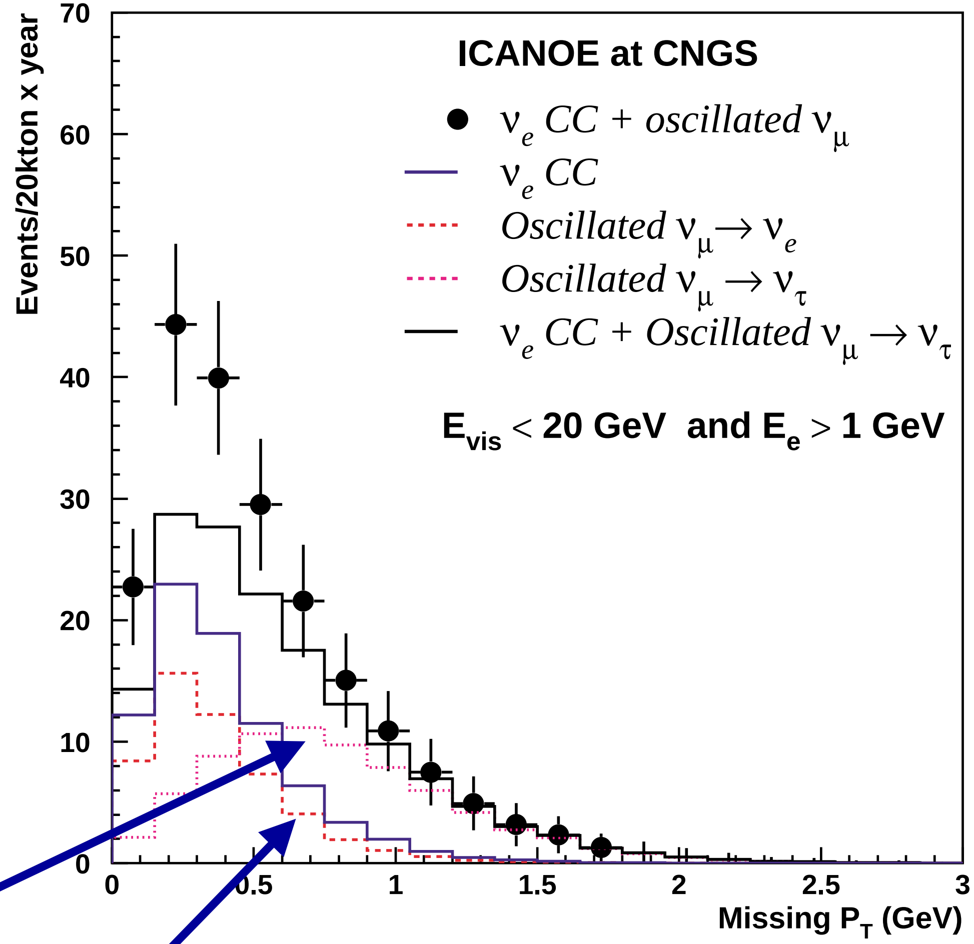
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \Delta^2{}_{32}$$

Δm^2_{32}=3.5x10^{-3} eV^2; $\sin^2 2\theta_{23}$ = 1 ; $\sin^2 2\theta_{13}$ = 0.05

Total visible energy



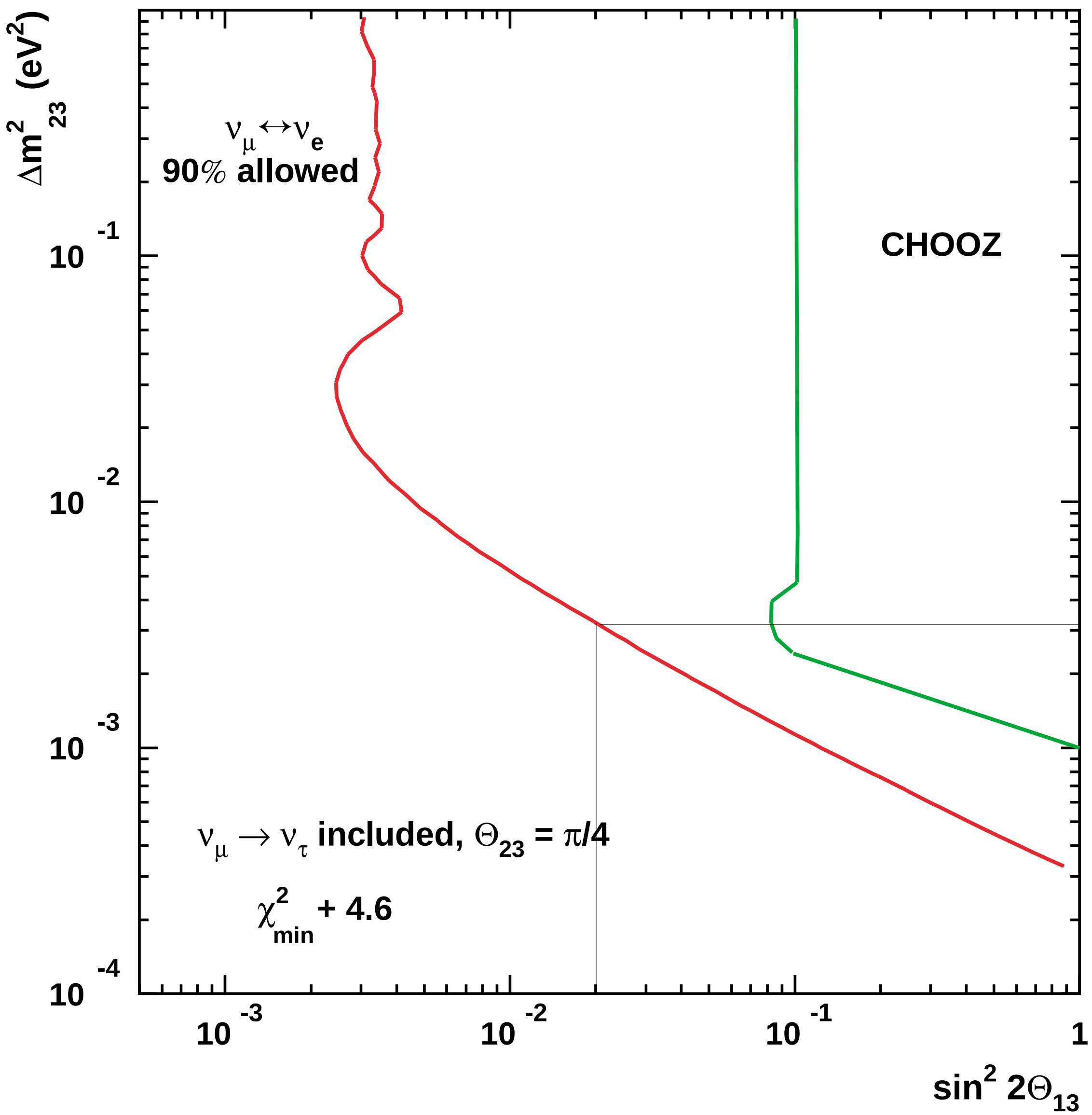
Transverse missing P_T



$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2{}_{32}$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\Delta^2{}_{32}$$

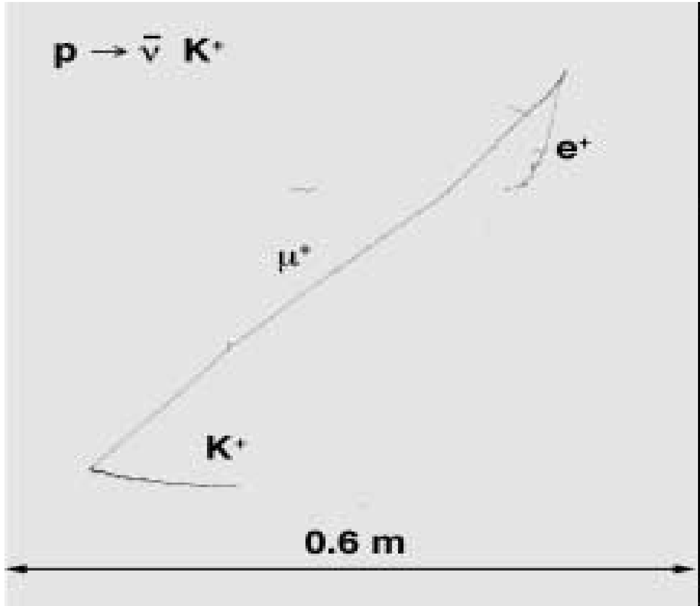
Sensitivity to θ_{13} in three family-mixing



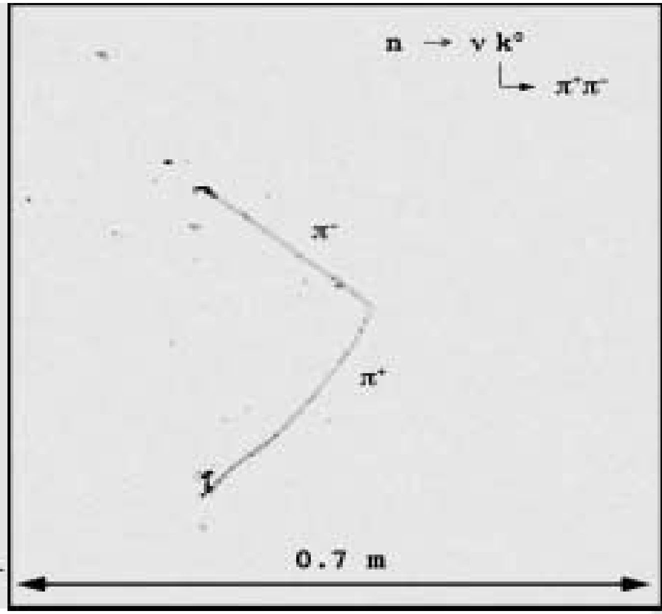
- Sensitivity to $\nu_\mu \to \nu_e$ oscillations in presence of $\nu_\mu \to \nu_\tau$ (three family mixing)
- Factor 5 improvement on $\sin^2 2\theta_{13}$ at $\Delta m^2 = 3\text{x}10^{-3}$ eV^2
- Almost two-orders of magnitude improvement over existing limit at high Δm^2

Nucleon decay search

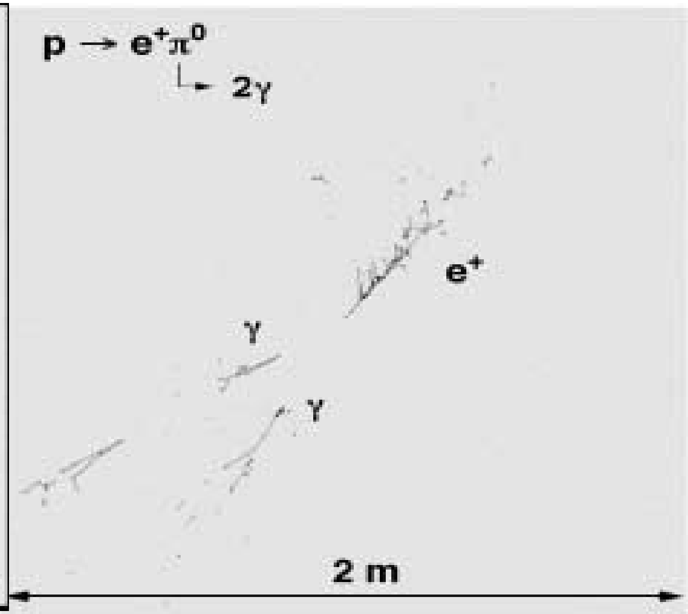
$p \to \nu K^+$ decay



$n \to \nu K^0$ decay



$p \to e^+ \pi^0$ decay



Thanks to excellent tracking and particle *id* capabilities

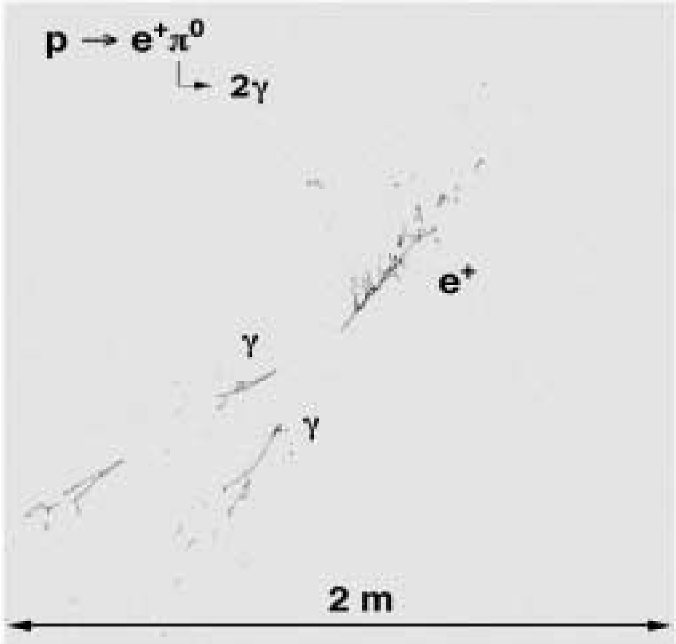
LAr unique tool for

Extremely efficient background rejection

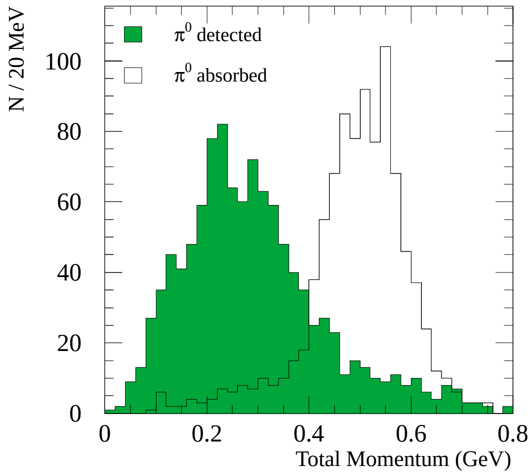
High detection efficiency

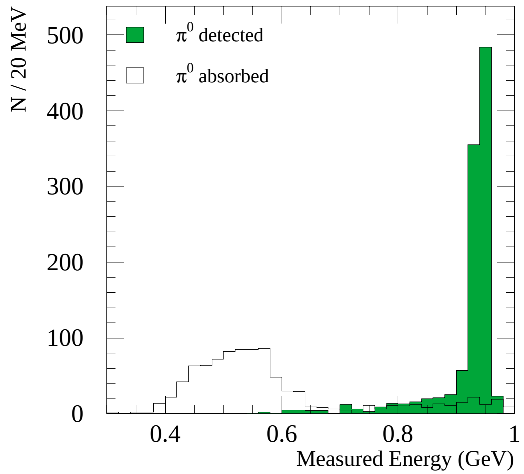
Bias-free, fully exclusive channel searches!

p→e⁺ π^0 decay kinematics



Nuclear effects: pion absorption and rescattering included (FLUKA)



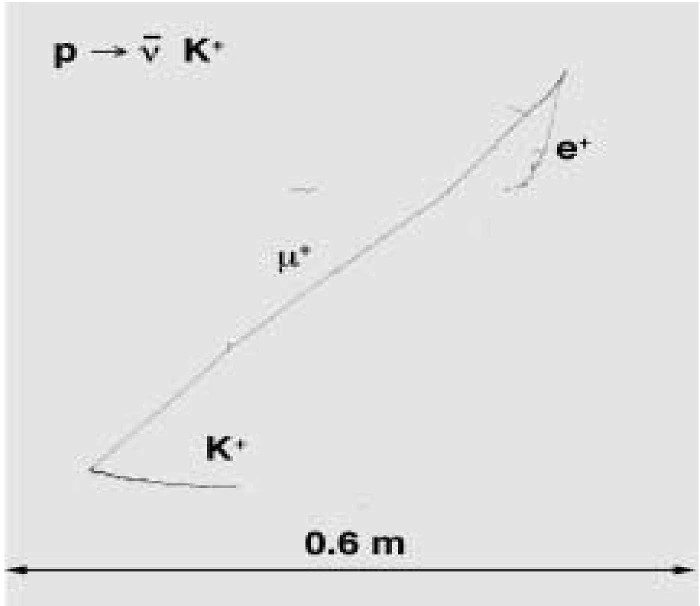


≈45% π^0 absorbed in Ar nucleus

Exclusive Channel Cuts	$p \to e^+ \pi^0$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One π^0	54.00%	6599	2136	15221	5789	8058	3095
One electron	54.00%	6567	2126	19	0	0	0
$T_{proton} < 100$ MeV	52.65%	2715	1448	4	0	0	0
0.93 GeV < Total E < 0.97 GeV	38.30%	28	17	0	0	0	0
Total Momentum < 0.46 GeV	37.50%	2	0	0	0	0	0

Exposure: 1000 kton x year

$p \to K^+\nu$ decay kinematics

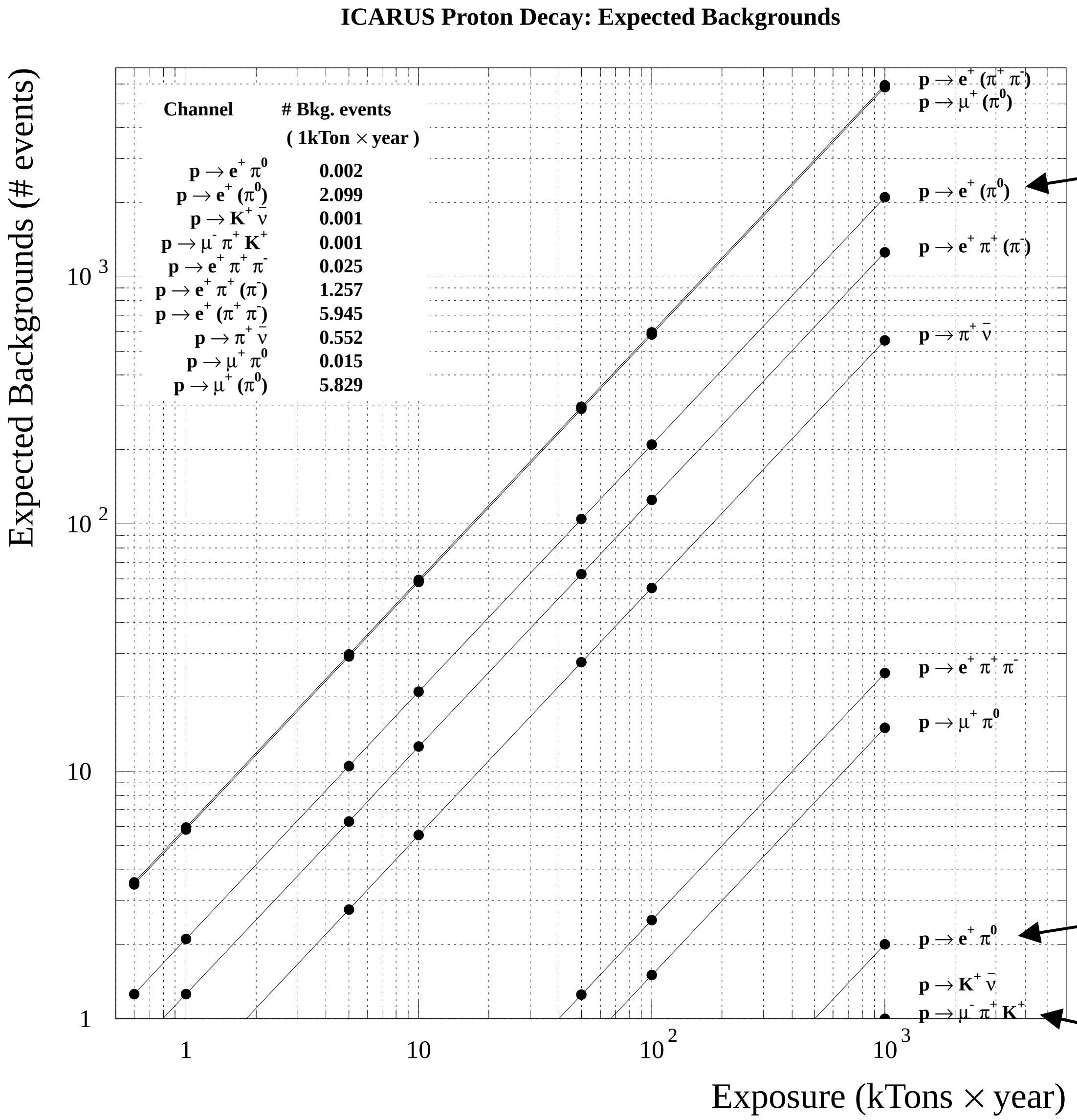


At least we see the kaon!

Cuts	$p \to K^+ \bar{\nu}$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One Kaon	97.30%	310	59	921	214	370	104
No π^0	97.15%	161	30	462	107	197	51
No electrons	97.15%	0	0	455	107	197	51
No muons	97.15%	0	0	0	0	197	51
No charged pions	97.15%	0	0	0	0	109	22
Total Energy < 0.8 GeV	97.15%	0	0	0	0	0	0

Exposure: 1000 kton x year

Proton decay: expected backgrounds vs channel



$p \to e^+ X$

$p \to e^+ \pi^0$

$p \to K^+ \nu$

↑1 Mton x yr

Extremely good exclusive signal signatures

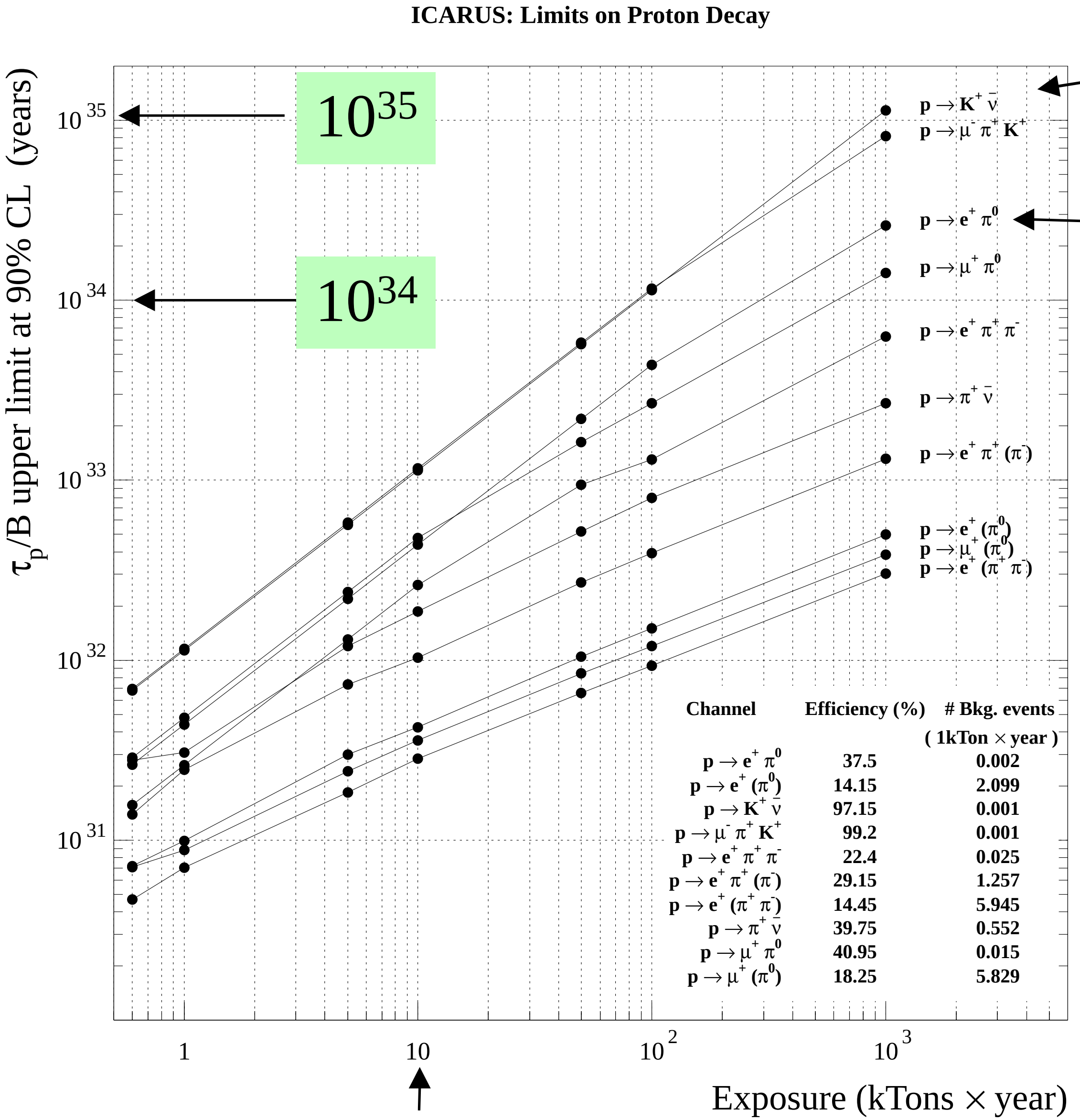
⇒ Excellent background rejection

Discovery with a single event!

Nuclear effects in backgrounds: fully embedded in *FLUKA* nuclear model

André Rubbia, ETH/Zürich, ICARUS Collaboration, 17/2/01

Sensitivity vs exposure



Channel	Efficiency (%)	# Bkg. events (1kTon × year)
$p \to e^+ \pi^0$	37.5	0.002
$p \to e^+ (\pi^0)$	14.15	2.099
$p \to K^+ \bar{\nu}$	97.15	0.001
$p \to \mu^- \pi^+ K^+$	99.2	0.001
$p \to e^+ \pi^+ \pi^-$	22.4	0.025
$p \to e^+ \pi^+ (\pi^-)$	29.15	1.257
$p \to e^+ (\pi^+ \pi^-)$	14.45	5.945
$p \to \pi^+ \bar{\nu}$	39.75	0.552
$p \to \mu^+ \pi^0$	40.95	0.015
$p \to \mu^+ (\pi^0)$	18.25	5.829

$p \to K^+ \nu$

$p \to e^+ \pi^0$

10 kton x yr

Extremely good exclusive signal signatures

⇒ Excellent background rejection

Discovery with a single event!

Nuclear effects in signal: fully embedded in *FLUKA* nuclear model

Exposure needed to reach PDG limit

Channel	Efficiency (%)	Background (1 kton×year)	PDG limit (10^{30} years)	Needed Exposure (in ktons×year)
$p \to e^+ \pi^0$	37.5	<0.1	1600	36.6
$p \to K^+ \bar{\nu}$	97.1	<0.1	670	6.0
$p \to \mu^- \pi^+ K^+$	99.2	<0.1	245	2.2
$p \to e^+ \pi^+ \pi^-$	22.4	<0.1	82	3.2
$p \to \pi^+ \bar{\nu}$	39.7	0.6	25	0.6
$p \to \mu^+ \pi^0$	40.9	<0.1	473	9.9
$n \to e^- K^+$	96.9	<0.1	32	0.3
$n \to e^+ \pi^-$	47.9	<0.1	158	2.3
$n \to \mu^- \pi^+$	48.2	<0.1	100	1.5
$n \to \pi^0 \bar{\nu}$	44.8	0.5	112	2.4

Given our poor knowledge of the physics at the GUT scale, we need to look for all possible channels, in unbiased, free of background searches.

Neutrino factory

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$\nu_\mu \rightarrow \nu_e \rightarrow e^-$	appearance
ν_μ	disappearance
$\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^-$	appearance
$\bar{\nu}_e$	disappearance
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu+$	appearance
$\bar{\nu}_e \rightarrow \bar{\nu}_\tau \rightarrow \tau+$	appearance

Plus their charge conjugates with μ^+ beam

Ideal detector should be able to measure **12 different processes**

⇨ Detect: μ^+, μ^-, e, NC, τ

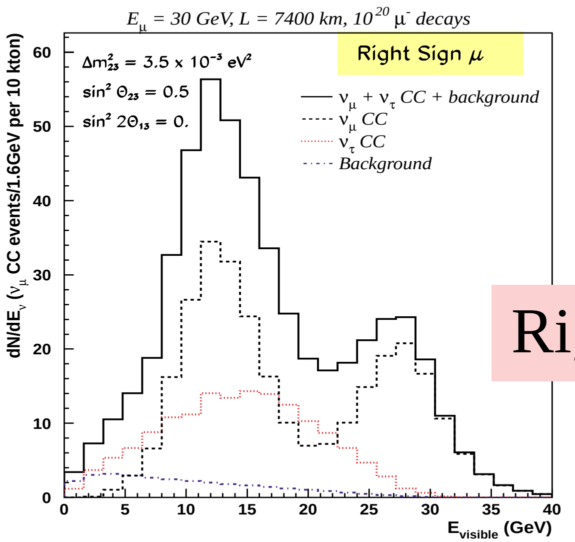
⇨ Various baselines

⇨ Various muon energies

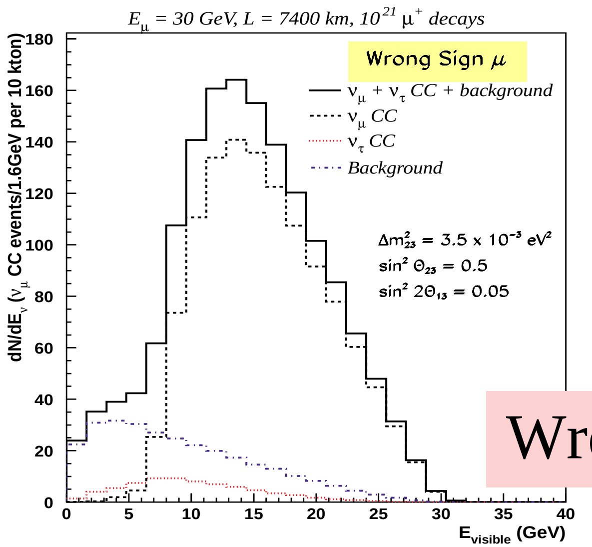
O(10^{21}) μ required

Baseline → Muon Energy →		L=732 km $E_\mu = 5$ GeV	L=2900 km $E_\mu = 30$ GeV	L=7400 km $E_\mu = 30$ GeV
μ^- 10^{21} decays	ν_μ CC	6150	72000	11300
	ν_μ NC	1590	20600	3400
	$\bar{\nu}_e$ CC	2150	27600	4370
	$\bar{\nu}_e$ NC	630	9950	1500
μ^+ 10^{21} decays	$\bar{\nu}_\mu$ CC	2450	31900	5000
	$\bar{\nu}_\mu$ NC	750	11200	1750
	ν_e CC	5550	64500	9900
	ν_e NC	1350	18300	2900

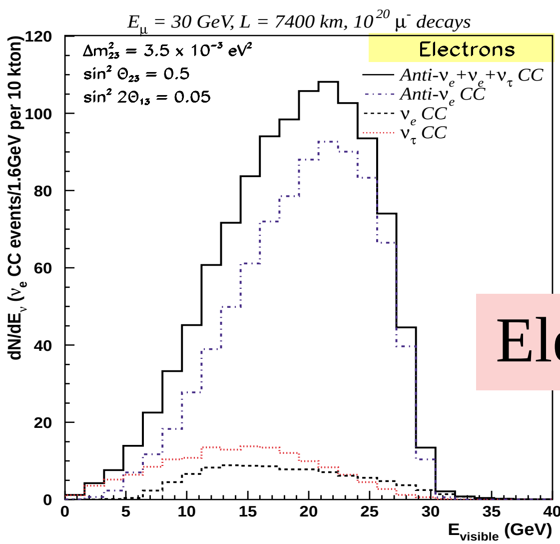
Event classes



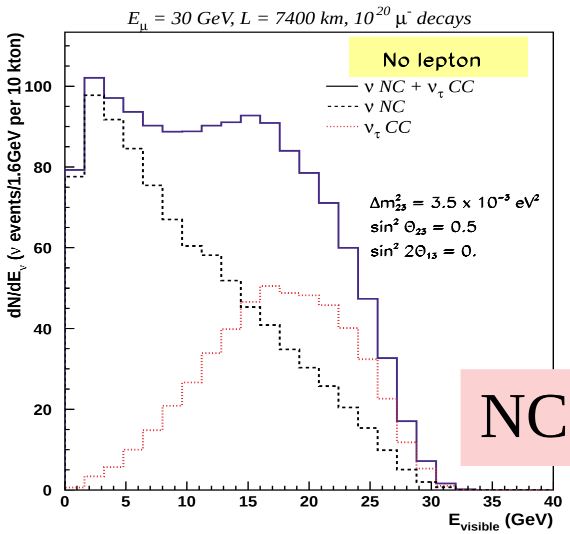
Right sign μ



Wrong sign μ



Electrons



NC-like

Combining all classes$\Rightarrow$ (over-constrained) sensitivity to all oscillations!

Conclusion

A very exciting field !