Summary of Neutrino 2000

focus on physics beyond Standard Model

1 - Neutrino masses & oscillations

2 - Quo vadis LSND?

decreasing $\sqrt{\Delta m^2}$

3 - Atmospheric neutrinos

4 - Solar neutrinos

emerging default option to refute: bimaximal??

5 - Future solar, long-baseline experiments

6 - Neutrinos & dark matter

7 - High-energy astrophysical ν's

8 - Neutrino factory

will neutrinos take over the world?

(thanks to Clarence, John, Mike et al. for their help

1 – Neutrino Masses & Oscillations

Why not? there is no good reason why $m_\nu = 0$

vanishing masses $\Leftrightarrow$ exact symmetries

e.g.: photon — e.g.: gauge invariance, Q_{em}

There is no massless gauge boson coupling to lepton number

$\Rightarrow$ do not expect lepton number conserved

"L" cf string theory (Witten)

$\Rightarrow$ ν mass possible

e.g. $m_\nu \, \nu \cdot \nu$ $\quad \Delta L = 2$

generic feature of Grand Unified Theories

even possible in the Standard Model: (Barbieri + JE + Gaillard)

$$\frac{1}{M} \nu H \cdot \nu H \quad \Rightarrow \quad m_\nu = \frac{\langle 0|H|0\rangle^2}{M}$$

M: some heavy mass scale $\gg m_W$

H: Higgs field

very small?

not so small in M theory: $M \ll m_P$

Neutrino Masses in GUTs

(Mohapatra

generic seesaw mechanism:

$$(\nu_L, \nu_R) \underbrace{\begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix}}_{= O(m_{q,\ell})} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

3 generations

right-handed singlet ν

diagonalization: $m_\nu = m \frac{1}{M} m^T$

naturally small if $M \sim m_{GUT}$:

e.g., $m \sim 10$ GeV, $M \sim 10^{13}$ GeV $\Rightarrow m_\nu \sim 10^{-2}$ eV

$\rightsquigarrow$ leptogenesis?

also expect mixing à la CKM:

(Maki + Nakagawa + Sakata)

$$V_{MNS} = V_\ell V_\nu^\dagger$$

diagonalizing m_ℓ diagonalizing m_ν

Mixing angles need not be small

cf quark, lepton masses?

different powers of ϵ?

diagonalize M?

$$\begin{pmatrix} \epsilon^n & \epsilon^m & \epsilon^p \\ \epsilon^m & \epsilon^q & \epsilon^r \\ \epsilon^p & \epsilon^r & 1 \end{pmatrix}$$

Neutrino Masses in Extra Dimensions

(Dienes

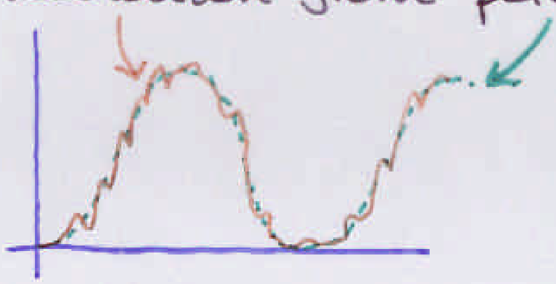
- many excited Kaluza-Klein states coupled to ν_L?

$$\begin{pmatrix} 0 & m & m & m & \cdots \\ m & M_1 & 0 & 0 & \\ m & 0 & M_2 & 0 & \\ m & 0 & 0 & M_3 & \\ \vdots & & & & \ddots \end{pmatrix} \otimes \text{flavour}$$

- naturally light neutrinos

  small Yukawa coupling? related to $R_{extra\,d}$?

- possible deviation from periodic oscillation:



much new parameter space to explore!

in String-Inspired/Derived Models

← intermediate GUT — extra d

- many singlet massive states

(J.E. + Leontaris + Lola + Nanopoulos

$$\begin{array}{cc} & \begin{array}{cc} 3 & N \gg 3 \end{array} \\ \begin{array}{c} 3 \\ N \gg 3 \end{array} & \left(\begin{array}{c|c} 0 & 1, \epsilon, \epsilon^2, \ldots \\ \hline 1, \epsilon, \epsilon^2, \ldots & \mathcal{M} \end{array}\right) \end{array}$$

- more possibilities for large mixing?

Upper Limits on Neutrino Masses

Tritium β decay $\Rightarrow$ $m_{\nu_e} < 2.2$ eV

no problems with $m^2 < 0$ (Weinheimer

proposal to reach < 0.5 eV

puzzle of Troitsk anomaly (Lobashev

$\pi \rightarrow \mu\nu$ decay $\Rightarrow$ $m_{\nu_\mu} < 190$ keV

time for new measurement:

$\downarrow$ by 1/20 ? (BNL g-2)

$\tau \rightarrow n\pi\nu$ decay $\Rightarrow$ $m_{\nu_\tau} < 15.5$ MeV (Roney

prospects to get $\lesssim 3$ MeV (B factories

May close cosmological window for ν_τ decay

Neutrinoless $\beta\beta$ decay $\Rightarrow$ (Ejiri

$\langle m_\nu \rangle_e \lesssim 0.2$ eV (Fiorini

$\sum m_{M_i} U^2_{ei}$ (Baudis et al.

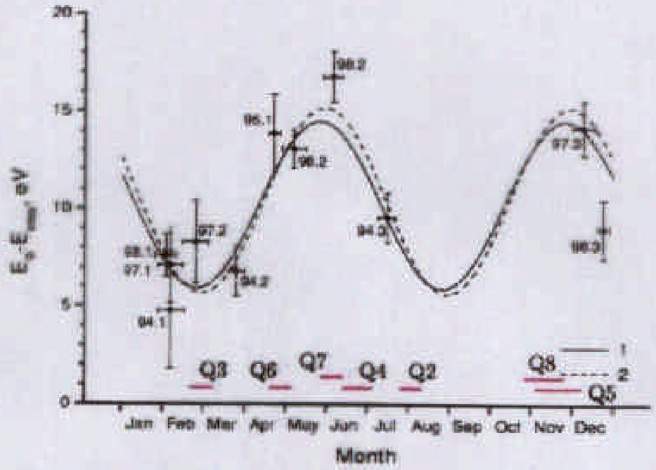
prospects to get $\lesssim 0.01$ eV

Beginning to impact ν mass models

present SN 1987a: $m_\nu \lesssim 20$ eV

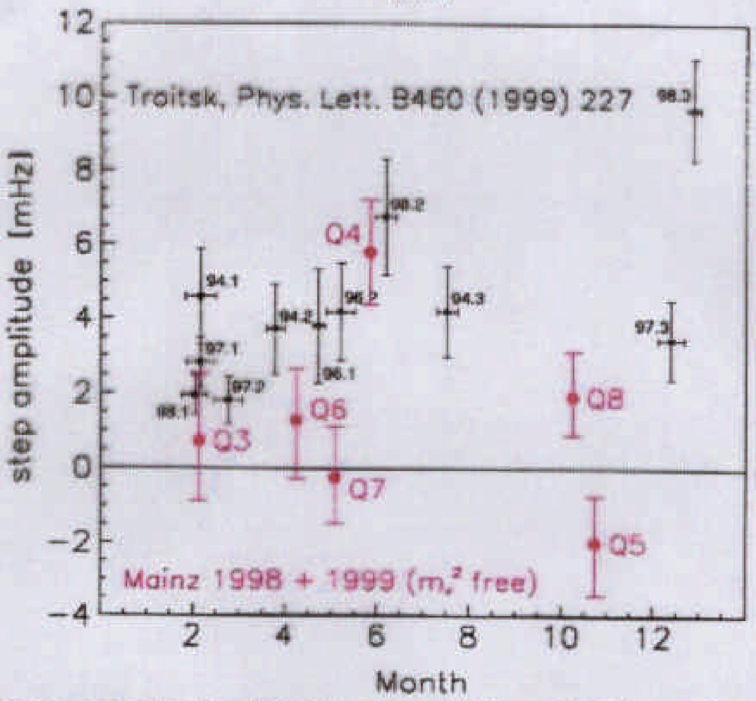
future $\longrightarrow$ $\lesssim 3$ eV ? (Scholberg

"Troitsk-anomaly" in Mainz data?



Troitsk
(Phys. Lett. B460 (1999) 227)

dates of Mainz measurements



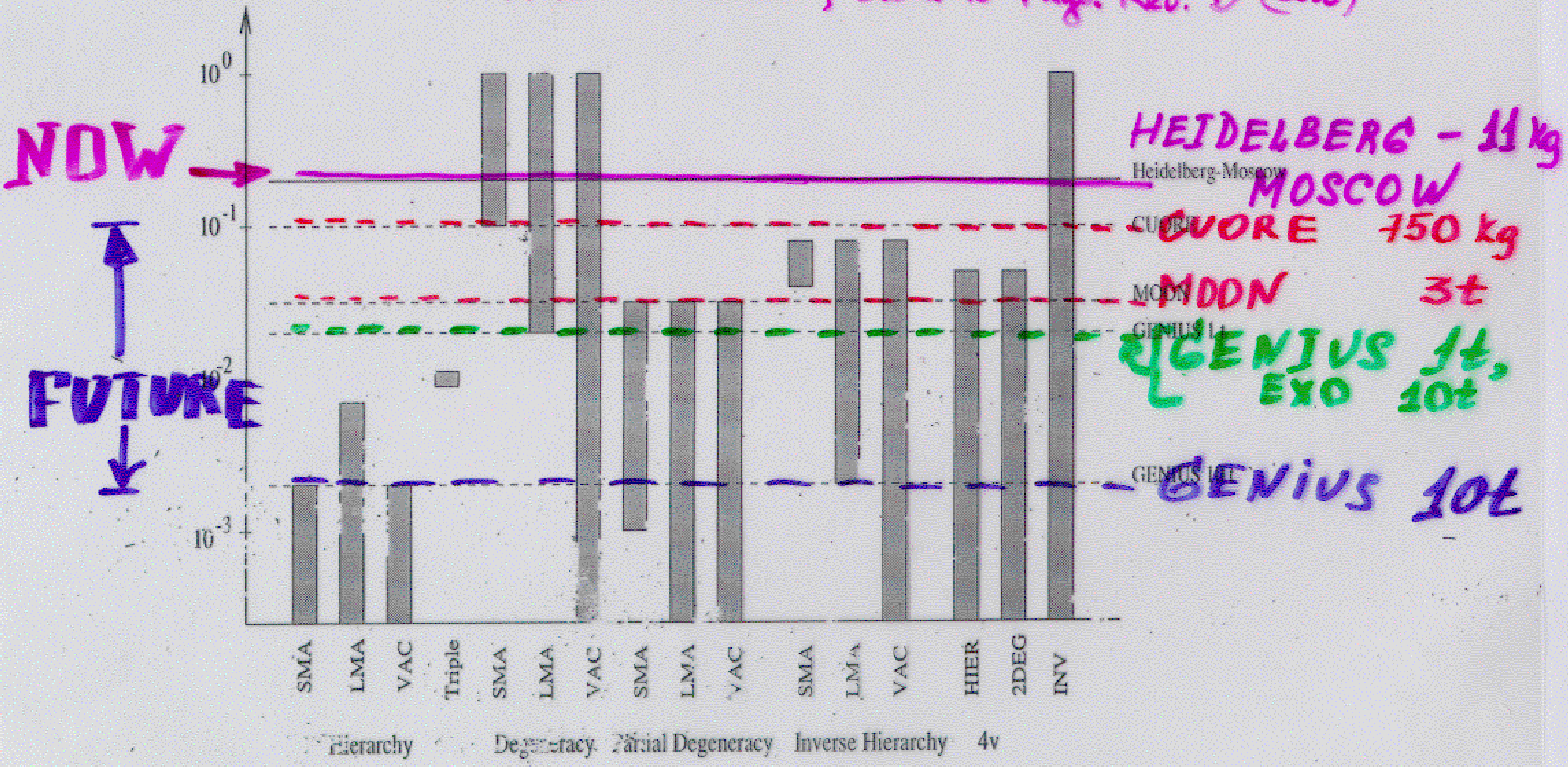
not supported

Mainz step amplitude at Troitsk prediction

- Clear support for the "Troitsk anomaly" from 1 (Q4) out of 6 data sets, is there something different for measurement Q4?
- But parameter space, favored by Troitsk, not fully excluded
- Clear contradiction to 0.5 y periodicity

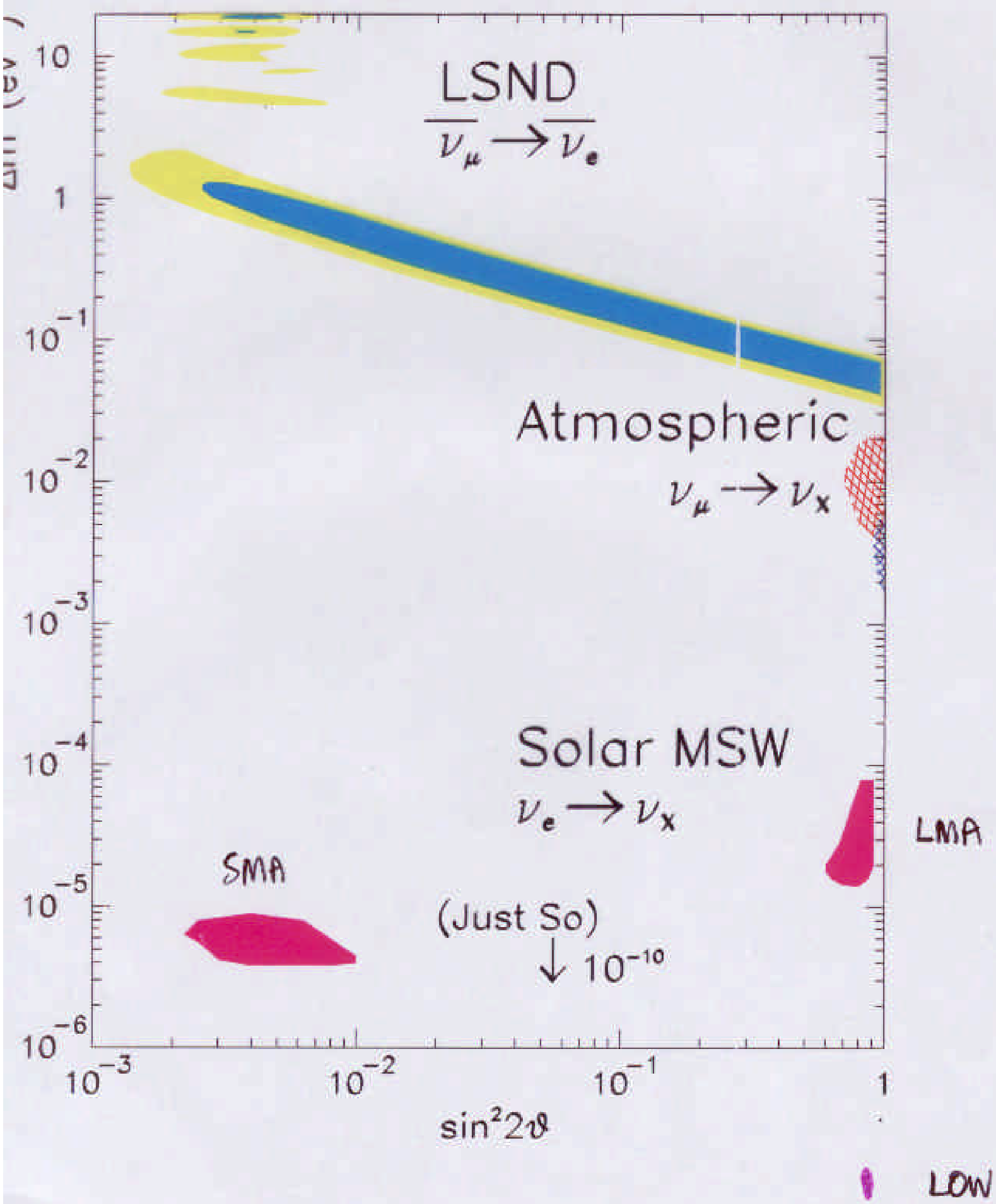
(Lobashov, Weinheimer)

from: H.V. KLAPDOR-KLEINGROTHAUS, H. PAES, A.Yu. SMIRNOV, subm. to Phys. Rev. D (2000)



Fits to ν Oscillations

before Neutrino 2000



2- Quo Vadis LSND?

- Reanalysis of full LSND data set: (Mills

  decay at rest ⊕ decay in flight

  ↘ 32.7 ± 9.2 events @ $R_\gamma > 10$

- Neither confirmed nor excluded by KARMEN (*) (Eitel

  Global analysis very desirable

  likelihood function in plane

- Definitive test will be made by MiniBooNE (Bazarko

  same L/E, but ν_μ @ 1 GeV

  starting in December 2001

- Possible follow-up by BooNE

- Opportunity for ORLaND (Avignone

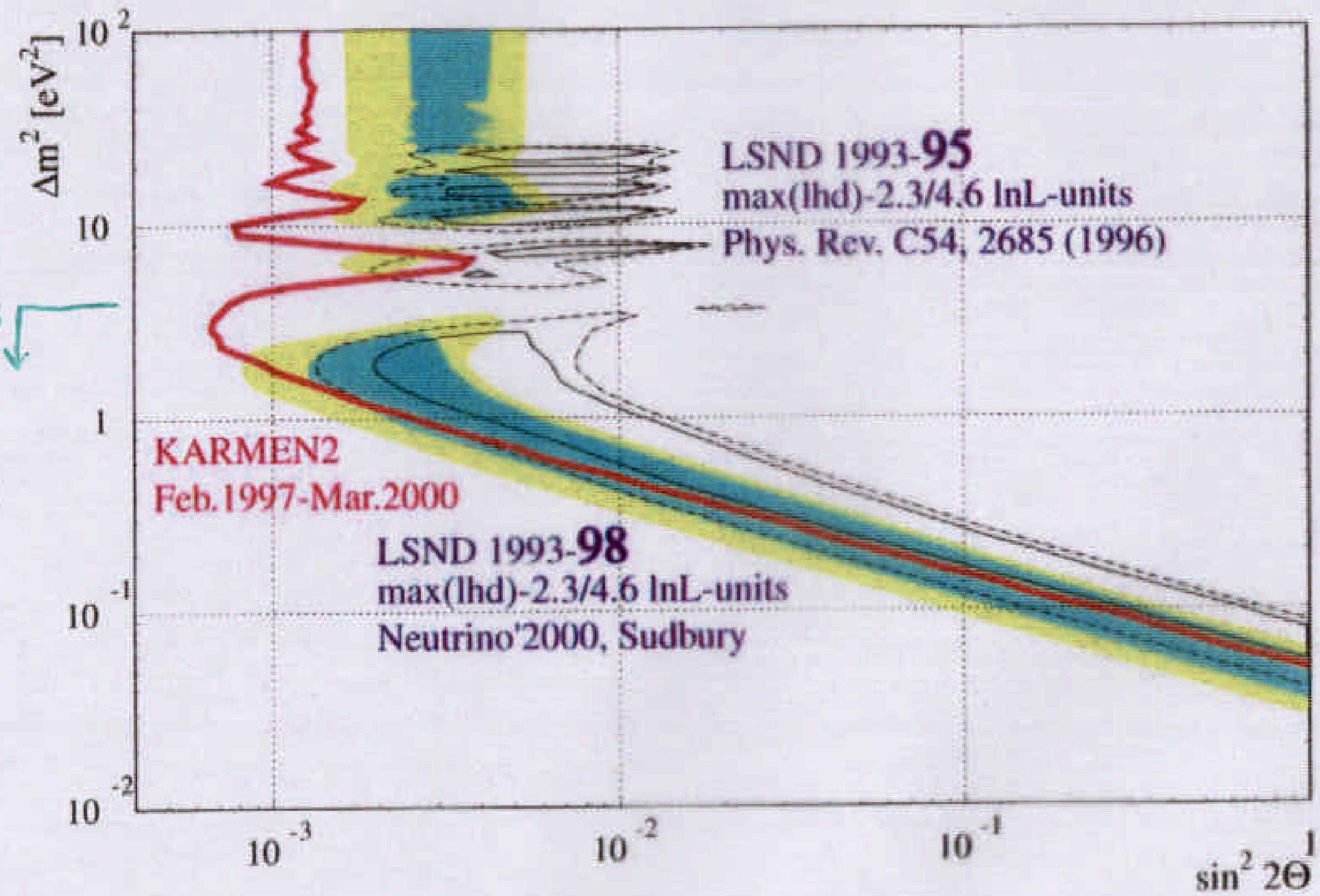
  $\exists$ adequate follow-up

(*) No further evidence for timing anomaly

LSND favored regions

constraint
from r-process
in SNae

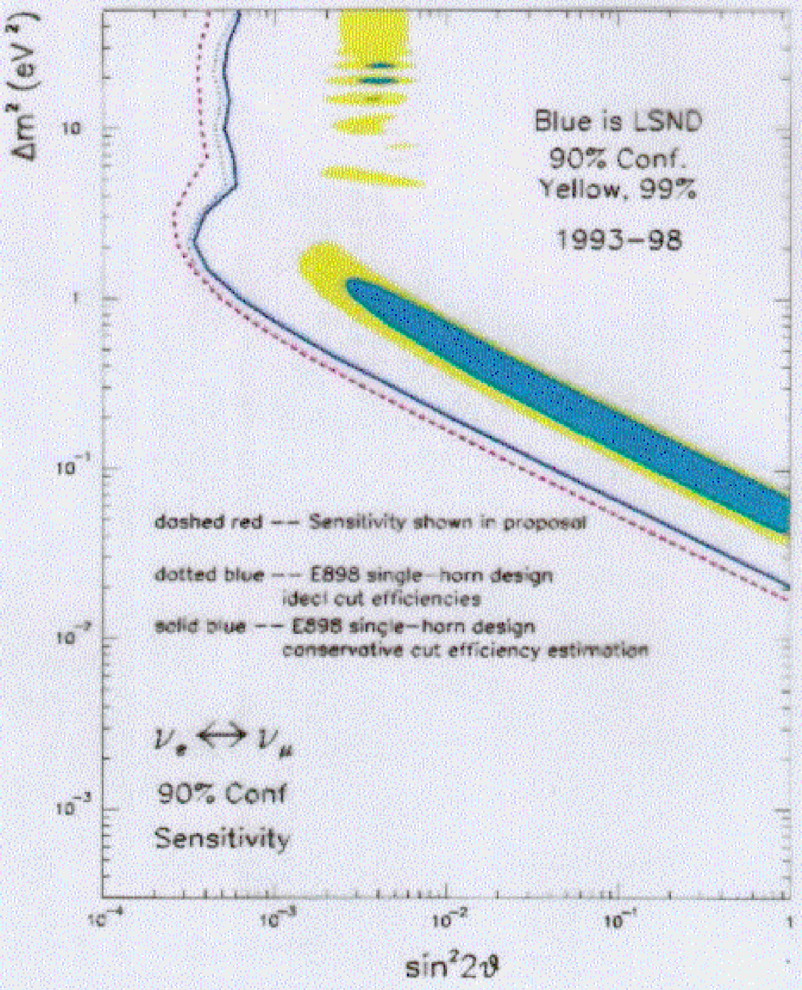
Qian)
Mezzacappa)
Prakash)



(Mills
(Eitel

Eitel - 09

MiniBooNE expected sensitivity

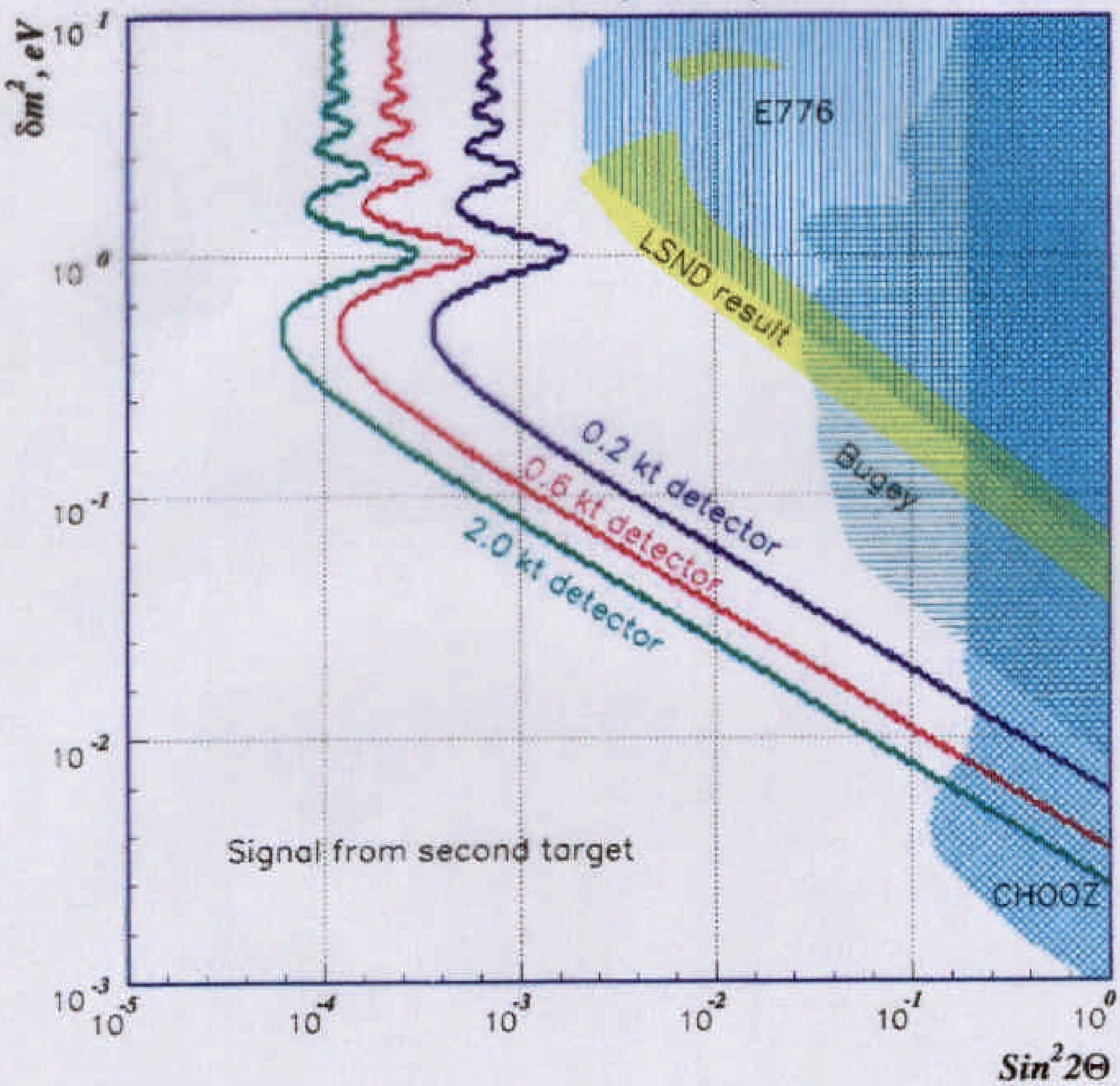


Final horn design, most conservative mis-id estimate, one calendar year of running

(Bazarko

Tektronix Tektronix Tektronix

ORLaND, limit after 3 y at 2 MW



Avignone

DeRuj 12

(De Rujula

3 - Atmospheric Neutrinos

- Improved understanding of 'beams'

  primary flux (AMS, BESS

  μ measurements (π production: HARP

  3-dimensional simulations (Lipari

  Conclusions robust: bias in parameters?

  small (Sobel

- Impressive statistics

  Plenty of smoking guns up/down, zenith $\angle$,...

- Several experiments

  Super-K, Soudan 2, MACRO but BUST ?
  (Sobel) (Mann) (Barish) (Mikheyev

  Preference for $\nu_\mu \to \nu_\tau$ @ 99% c.l. ($\nu_\mu \to \nu_e < 0.1$)

  zenith $\angle$ distributions of $\left\{ \begin{array}{l} \text{NC-enriched multi-ring} \\ E > 5\text{GeV PC} \\ \uparrow \mu \end{array} \right.$ (Sobel

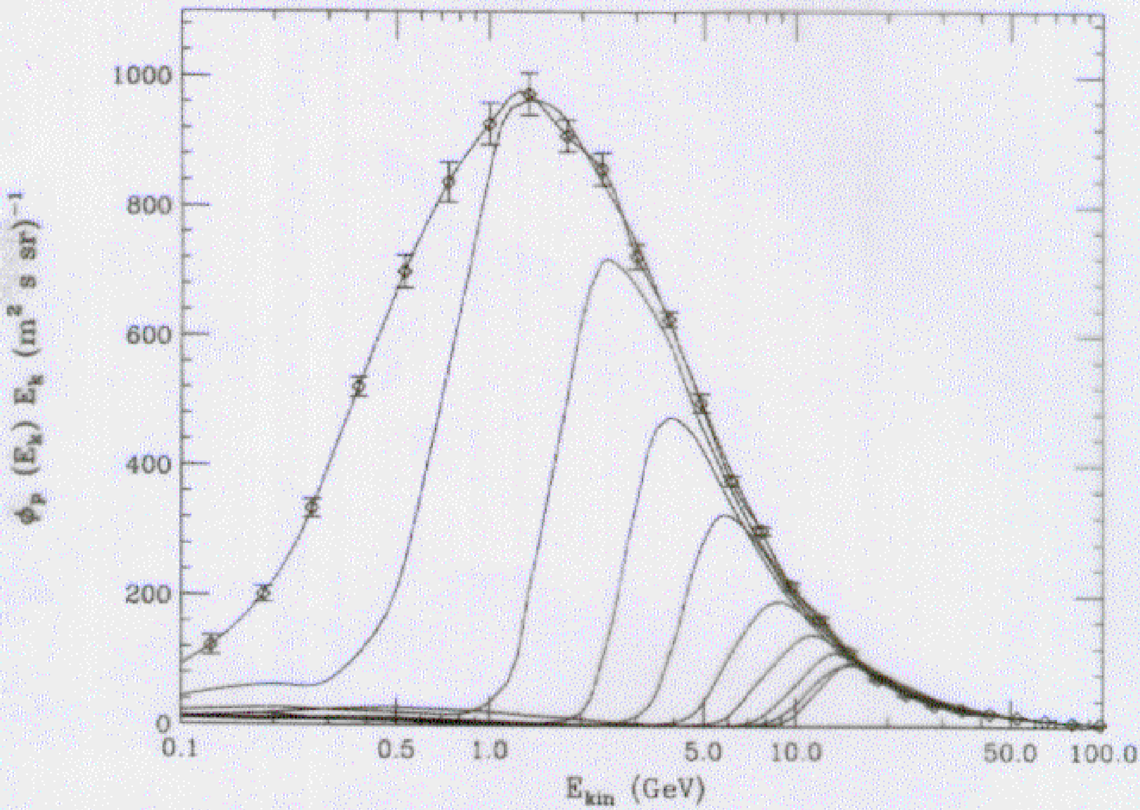
  how about π^0 production?

  from ν_τ, not ν_s

  data from K2K near detector needed

  BUT....

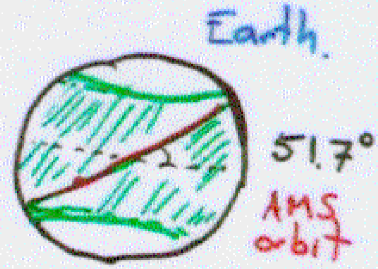
$\boxed{\text{AMS}}$ measurement of the proton flux (Lipari



Measurement in different regions of Magnetic Latitude.
$E_{\rm kin}(\text{threshold}) \simeq 0.3$ GeV.

$$\Phi(\text{polar}) \simeq 2470 \ \ (\text{m}^2\,\text{s}\,\text{sr})^{-1}$$

$$\Phi(\text{equator}) \simeq 140 \ \ (\text{m}^2\,\text{s}\,\text{sr})^{-1}$$



$\Phi_{\rm primary}(\text{equator}) \simeq 100 \ (\text{m}^2\,\text{s}\,\text{sr})^{-1}, \quad \Phi_{\rm albedo}(\text{equator}) \simeq 40 \ (\text{m}^2\,\text{s}\,\text{sr})^{-1}$

Effect of 3-Dimensional Atmospheric ν Simulation

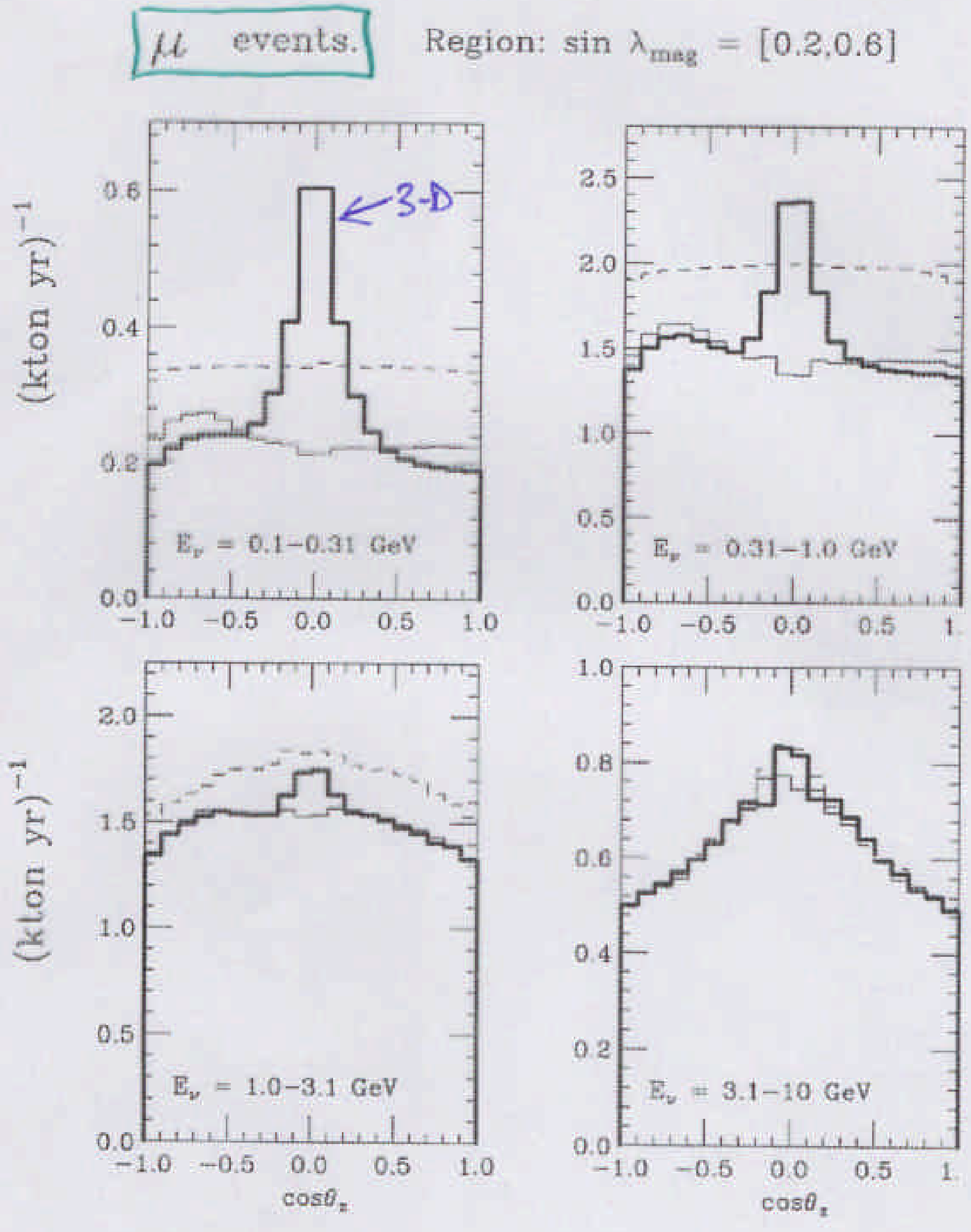
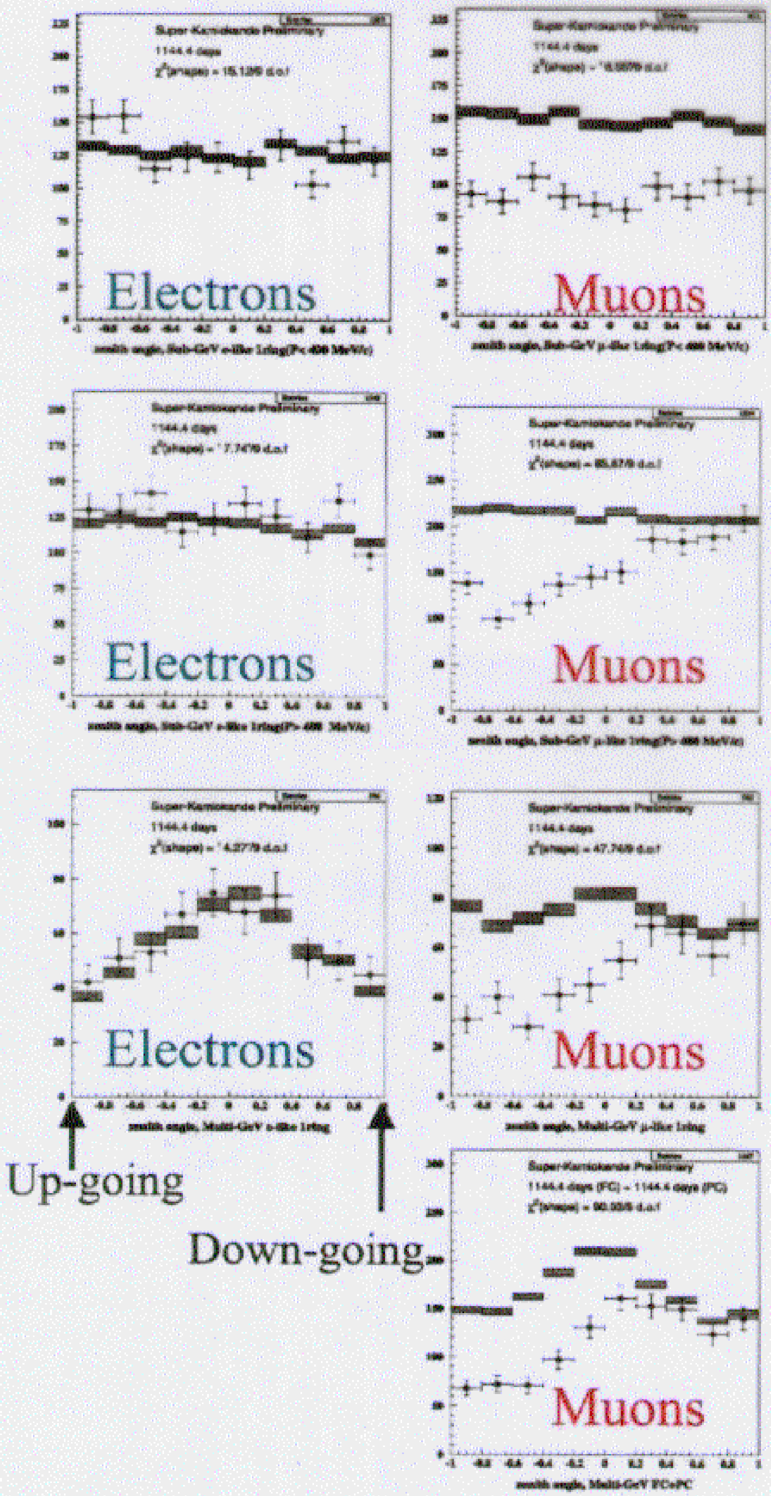


Figure 7: Average zenith angle distributions for μ-like events for detectors located in positions on the Earth with magnetic latitude $\sin\lambda_M = [0.2, 0.6]$. The four panel are for different neutrino energy intervals. The three histograms are for: fully 3–D calculation (thick), 1–D calculation (thin), 1–D without geomagnetic effects (dashed).

(Lipari: hep-ph/0002282)

What do we see?

(Super-K: Sobel



Sub-GeV
E < 400 MeV

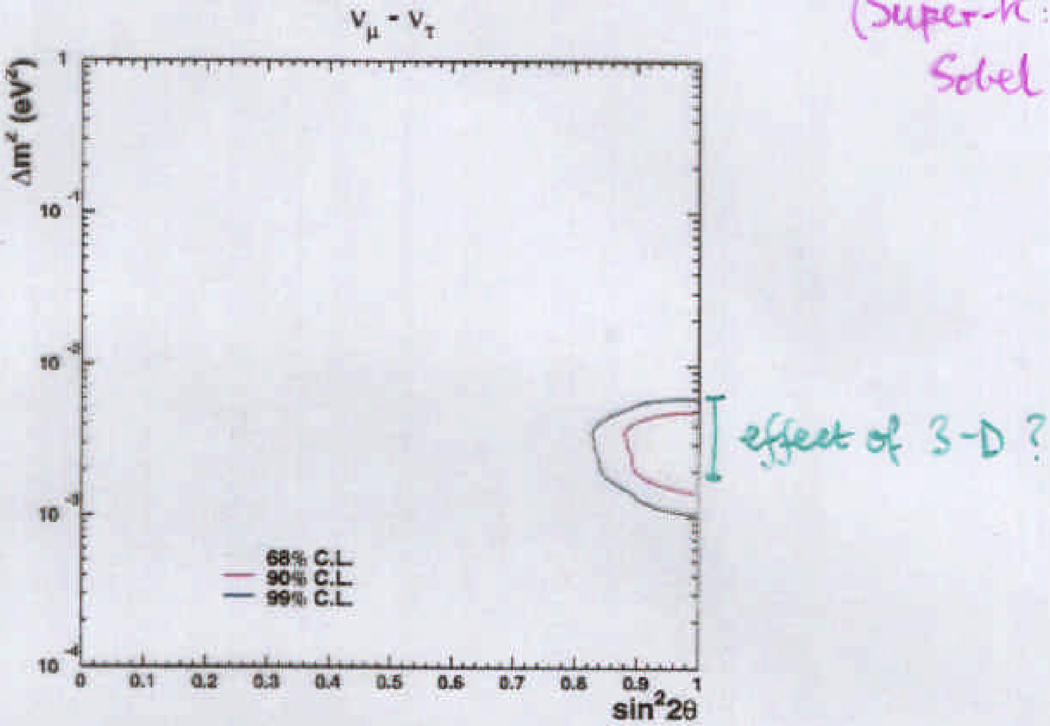
Sub-GeV
E > 400 MeV
E < 1.33 GeV

Multi-GeV
E > 1.33 GeV

FC+PC events
E > 1.33 GeV

Result of combined fit
FC,PC,UpMu

(Super-K: Sobel



Result of Oscillation Analysis (FC + PC + Upmu)

- Assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillation

Best fit :

χ^2_{min} = 135.3 / 152 d.o.f

at $(\sin^2 2\theta, \Delta m^2) = (1.01\ ,\ 3.2\times10^{-3}\ eV^2)$

(Including unphysical region)

χ^2_{min} = 135.4 / 152 d.o.f

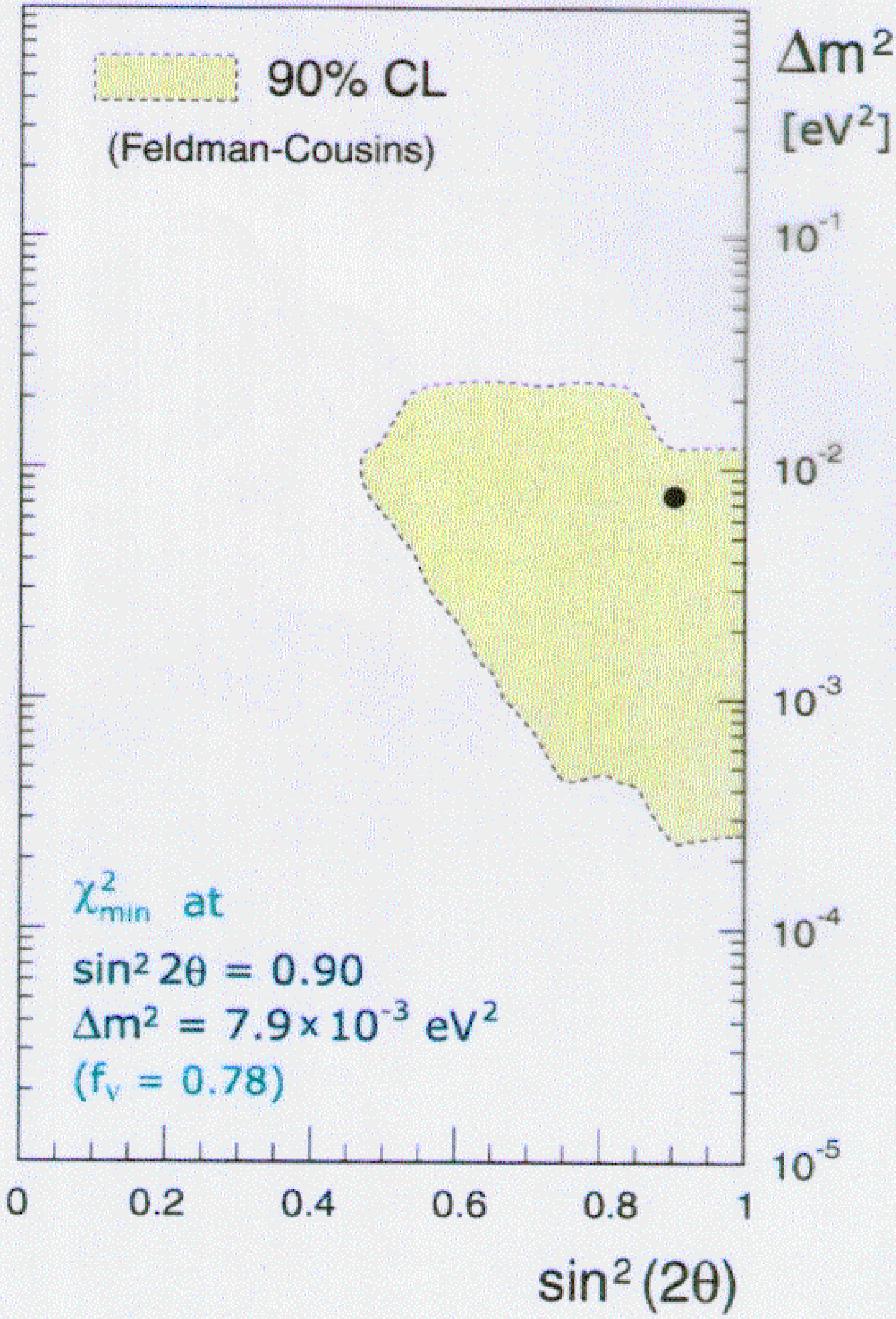
at $(\sin^2 2\theta, \Delta m^2) = (1.00\ ,\ 3.2\times10^{-3}\ eV^2)$

(Physical region)

- Assuming null oscillation

$\chi^2 =_{min}$ = 316.2 / 154 d.o.f

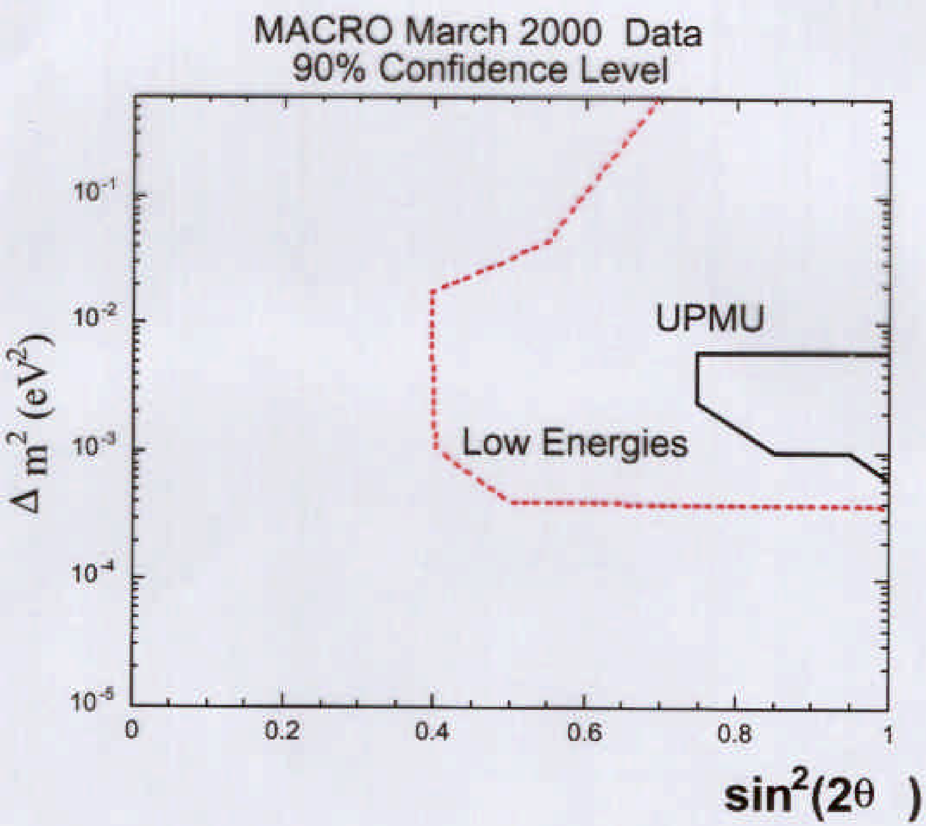
preliminary



(Soudan 2:
Mann

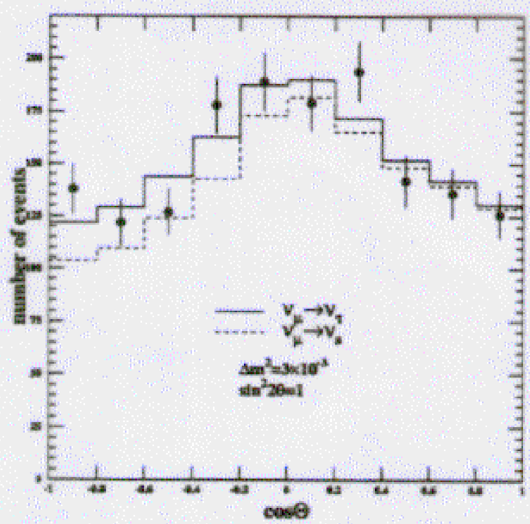
MACRO ν events: confidence level regions for $\nu_\mu \rightarrow \nu_\tau$ oscillation

(MACRO:
Barish



Zenith angle distributions

zenith angle distribution of N.C. enriched multi-ring events (1144da

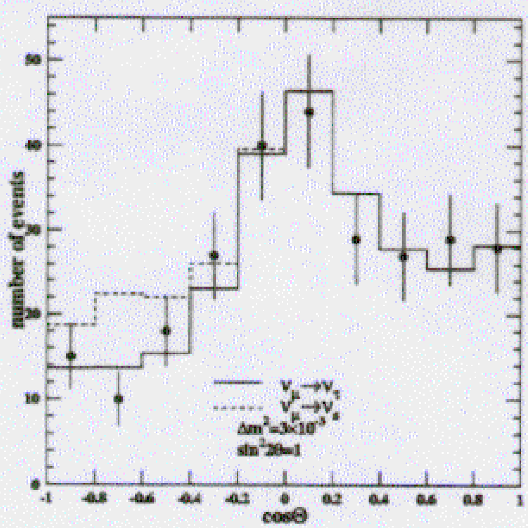


disfavour $\nu_\mu \to \nu_s$

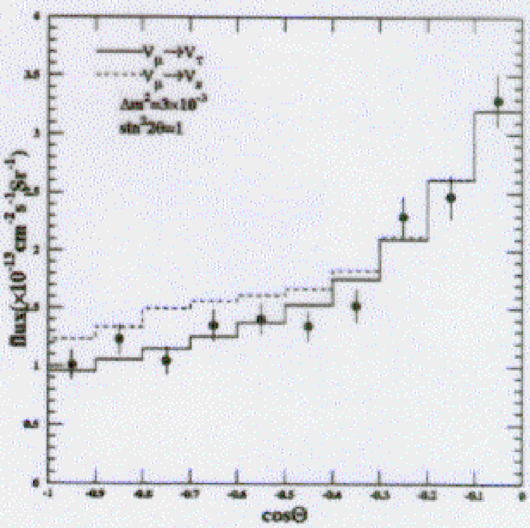
NC enriched multi-ring events

(Sobel

zenith angle distribution of high E (E_{vis}>5GeV) PC events (1144day



zenith angle distribution of upward through going μ events (1138da

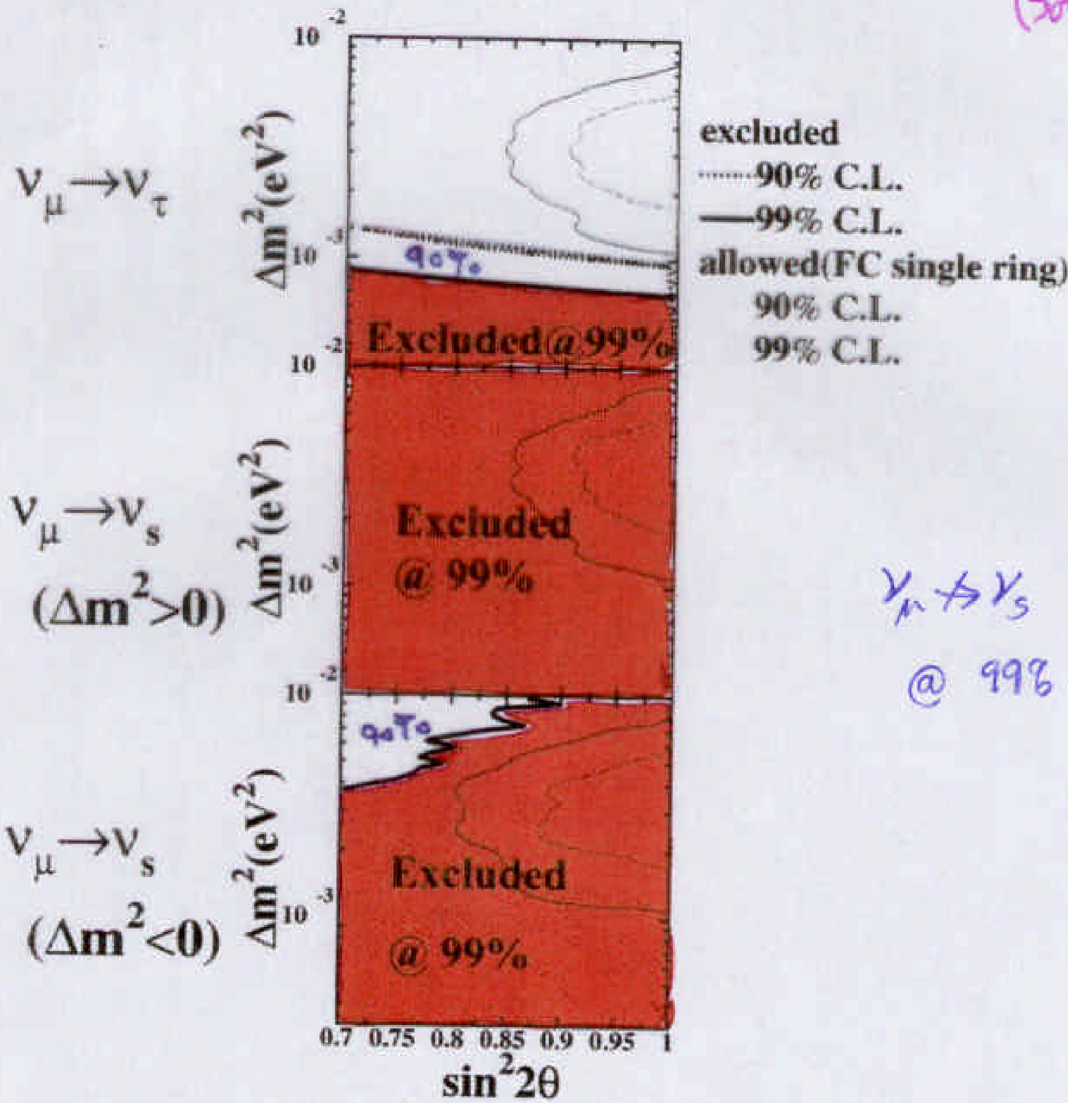


E_{vis}> 5 GeV PC events

Up mu events

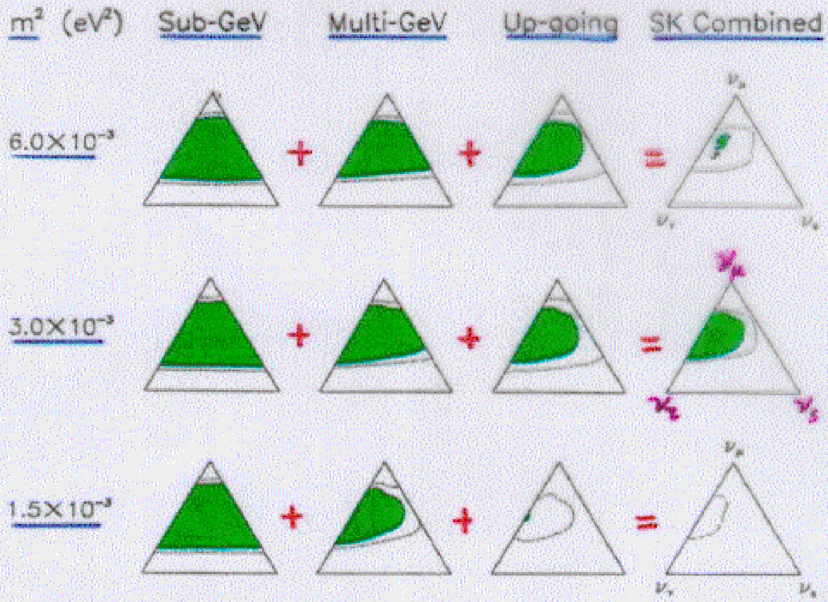
Excluded regions from combined analysis (multi+PC+UpMu)

(Sobel



$\nu_\mu \not\to \nu_s$ @ 99% c.l.

Fogli, E.L., Marrone : PRELIMINARY RESULTS
USING 61 KTy SK data (55 bins)



could be mixture
$\nu_\mu \to \nu_\tau$
$\nu_\mu \to \nu_s$

(Lisi

- Best fit at $\sim 3\times10^{-3}\,eV^2$, close to left side ($\sim \nu_\mu \to \nu_\tau$)
- Pure $\nu_\mu \to \nu_s$ (right side) disfavored @ 99% C.L.
- However, large $\nu_\mu \to \nu_s$ oscillations, in addition to $\nu_\mu \to \nu_\tau$, cannot be excluded (e.g., $\nu_\mu \to \frac{1}{\sqrt{2}}(\nu_s + \nu_\tau)$)
- At "high" m^2, nonzero $\nu_\mu \to \nu_s$ favored (reduces large μ suppression)
- Constraints increase with energy and s^2_ξ, due to effective mass term in matter

$$A_{eff} = 2\sqrt{2}\, G_F \frac{N_n}{2} \cdot E \cdot s^2_\xi$$

BUT ...

No evidence for τ appearance

super-K trying...

No evidence of oscillation pattern

Windows for theorists to speculate.

more ν species? (Lisi

change ν dynamics?

decay? decoherence? × equivalence?

$\underbrace{\text{decay? decoherence?}}_{\sim \text{indistinguishable?}}$

LE^n : $n = -1.06 \pm .14$

Motivations for future experiments (Geiser

improve upper limit on $\nu_\mu \to \nu_e$ (Mikaelyan
Krasnoyarsk

look for τ appearance ICANOE, MONOLITH

measure oscillation pattern MONOLITH

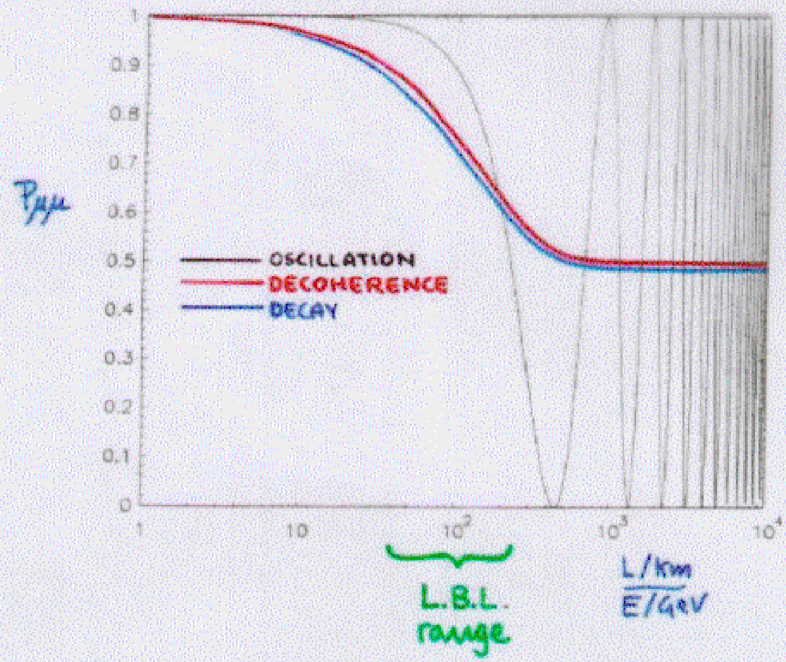
megaton detector? AQUA-RICH, UNO

LBL expts

also nucleon decay

So, the lack of periodicity in SK μ data can be interpreted in two ways:

- smearing of oscillation pattern
- signal of non-oscillatory new physics (decay, decoherence, ...)*



Lisi

→ Important to see at least one oscillation cycle (or the lack of it) in the energy and/or pathlength domain (LBL ?)

* Another example: Barbieri & al, $\nu_\mu \to \nu_{KK}$ in extra-dim. models

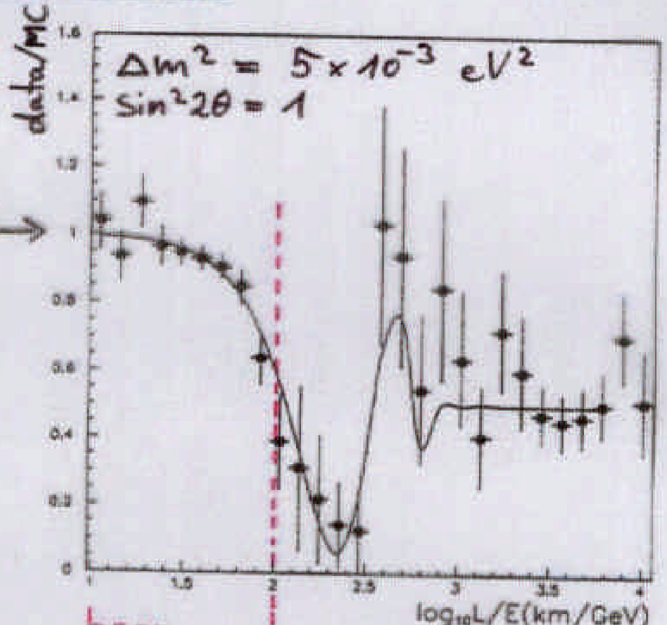
complementarity of atmospheric ν's + beam ν's

CERN/Gran Sasso beam ≥ 2005

<u>example</u>:

MONOLITH 2 years atm. + 1 year beam

normalized →



beam + atm. ⟵ ⟶ atm. only

caveat:

beam systematics?

(Geiser

ICANOE:

beam analysis (see talk A. Rubbia)
(bin-to-bin syst. error: 30%)
+ atmospheric analysis "à la Super-K"

⇒ combined fit

4 - Solar Neutrinos

Welcome to the new kids on the block!

SNO

(McDonald

beautiful events

clear CC signal: $\nu_e + d \to p + p + e^-$

clean E spectrum $\propto$ SSM

no sign of distortion, hep tail

clear ES signal: $\sum_i \nu_i + e^- \to \sum_i \nu_i + e^-$

see the Sun

even on a cloudy day

Phase I $\to$ end 2000

measure CC, ES rates (ratio) hope for 3σ?

Phase II: add salt, run for year

measure NC: $\sum_i \nu_i + d \to n + p + \sum_i \nu_i$

Phase III: add ^{3}He detectors

independent NC measurement

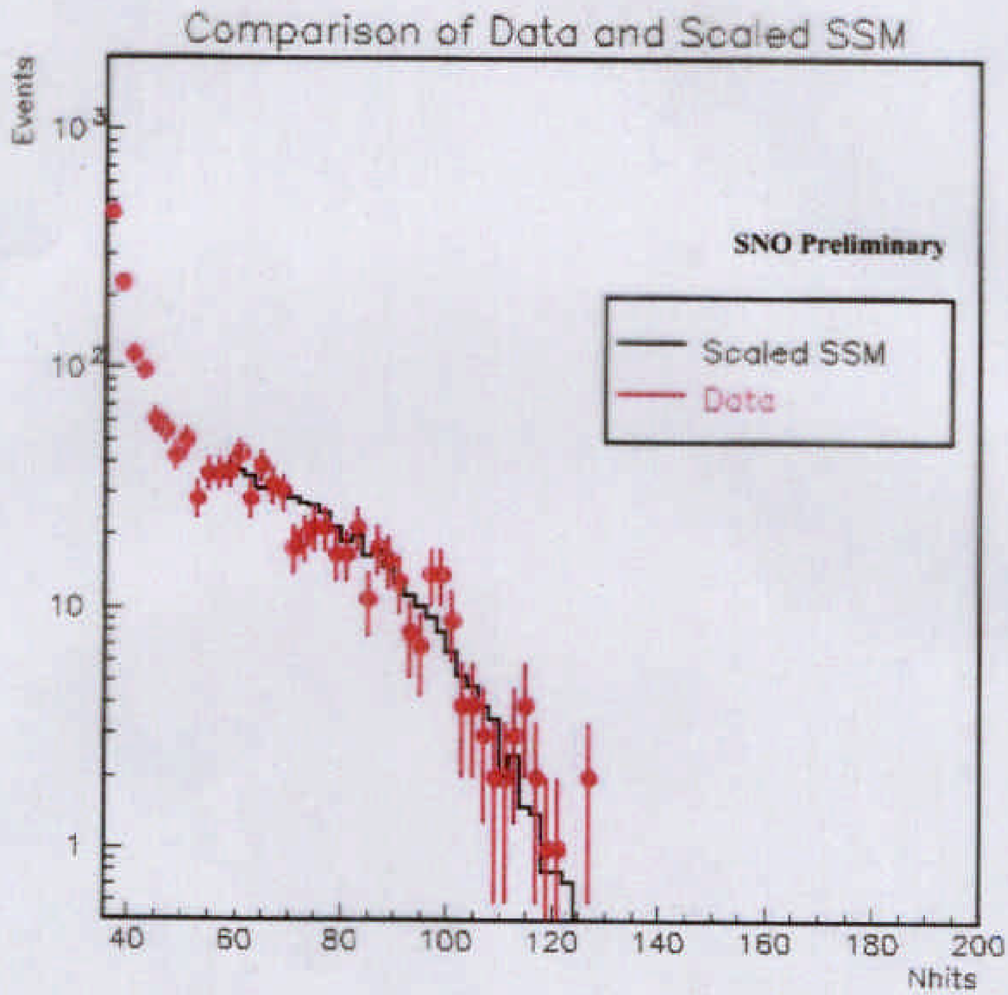
(Bellotti

GNO

with GALLEX $\Rightarrow$ $77.5 \pm 6.2^{+4.3}_{-4.7}$ SNU

McDon-- 2

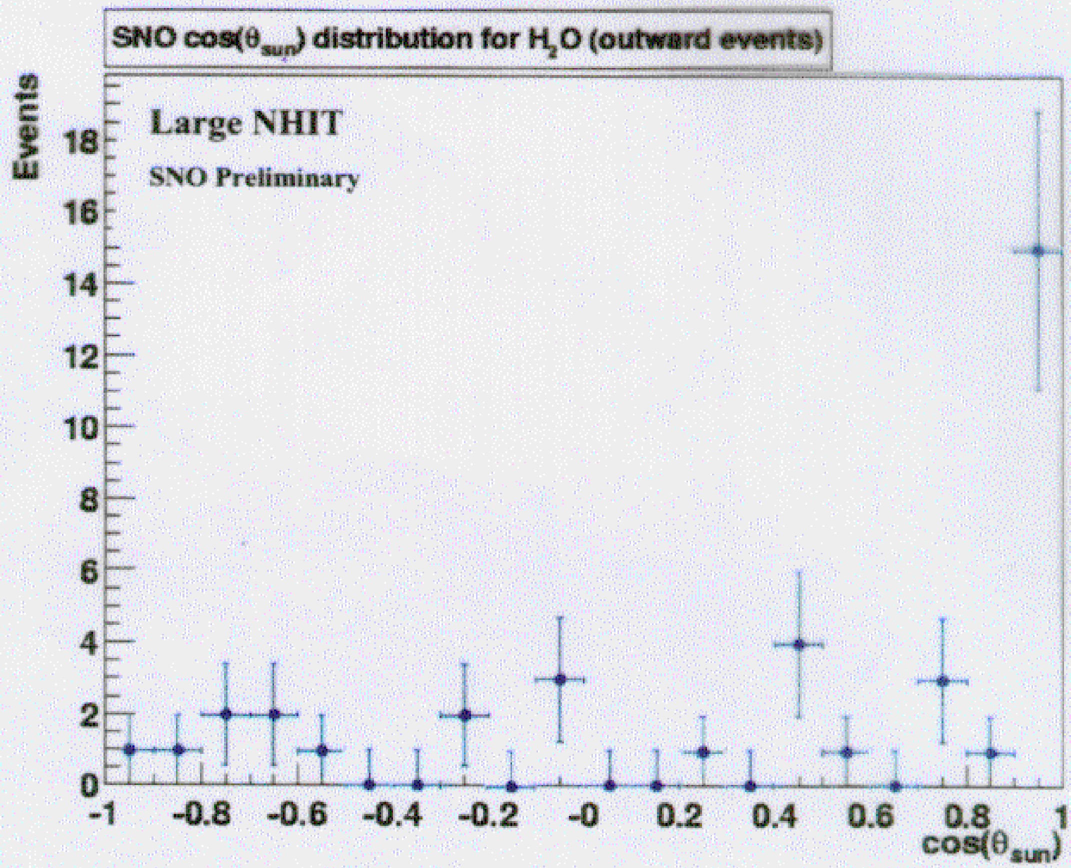
CC data



(SNO
(McDonald

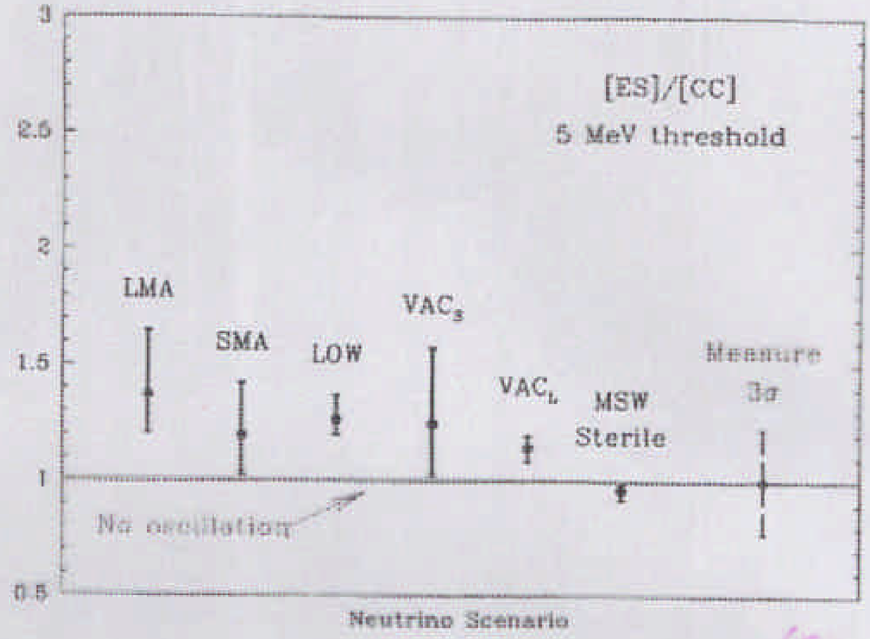
McDon~ 2

ES data

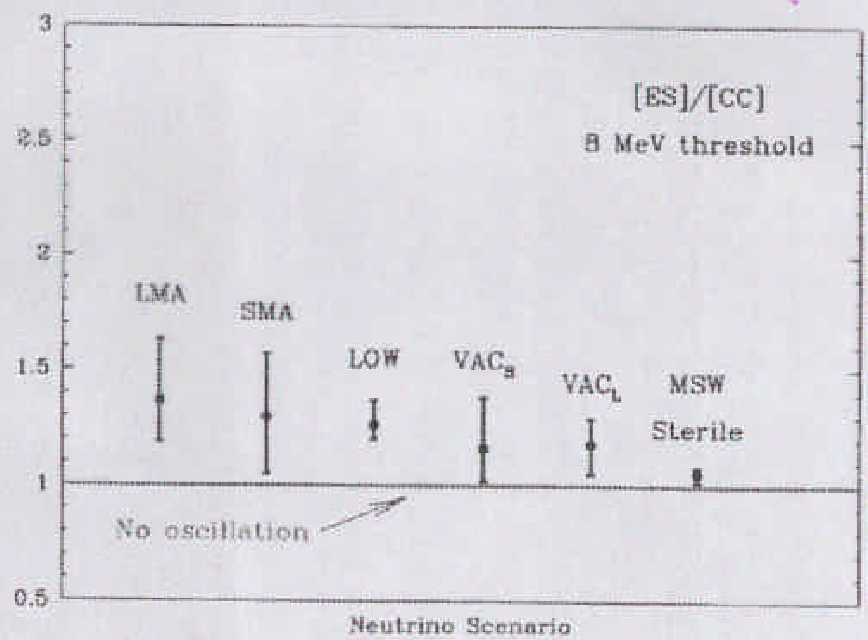


(SNO
(McDonald

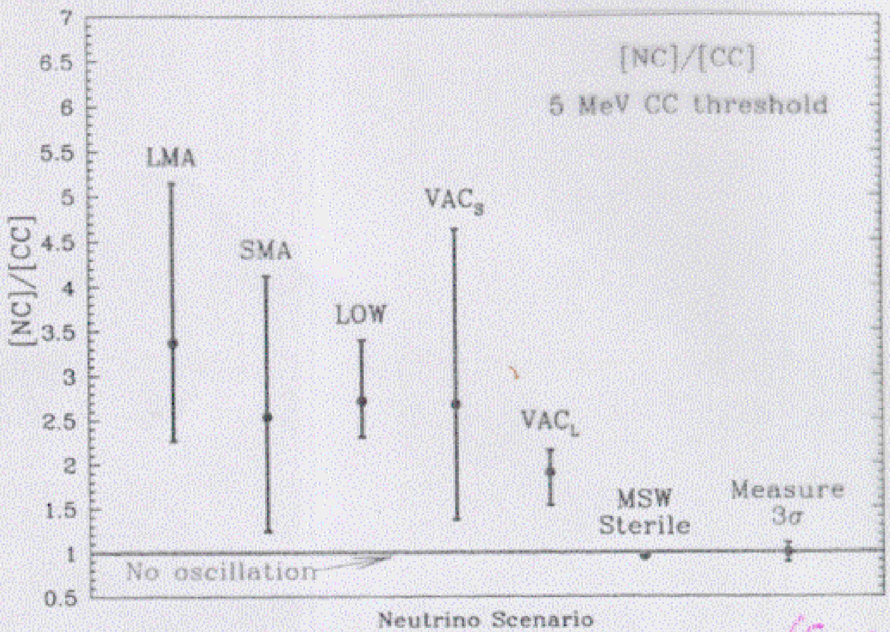
Potential of SNO Phase I



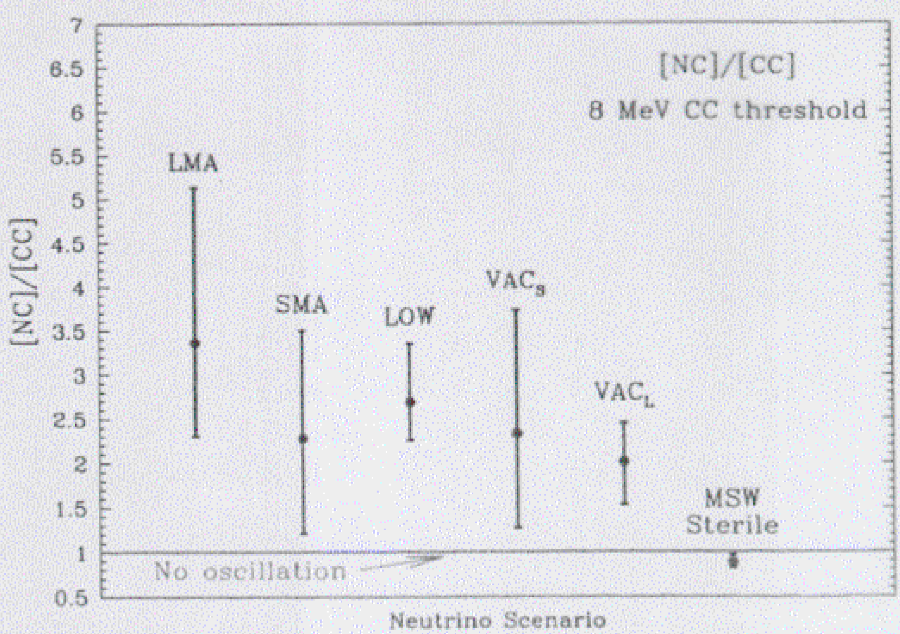
(Smirnov



Potential of SNO NC Measurement



(Smirnov



Super-Kamiokande

(Suzuki

- 1117 days, $E_{thr} \Rightarrow 5$ MeV, background ↓ 60%
- re-analysis of all data:

$$\frac{SK}{BP98} = 0.465 \pm 0.005 \,{}^{+0.016}_{-0.013}$$

- energy spectrum consistent with constant suppression: $\chi^2 = 13.7/17$ d.o.f.
- upper limit on hep neutrinos:

$$\frac{hep}{SSM} < 13.2 \quad (E > 18\,\text{MeV})$$

$\Rightarrow$ irrelevant in global fits

- reduced day-night effect:

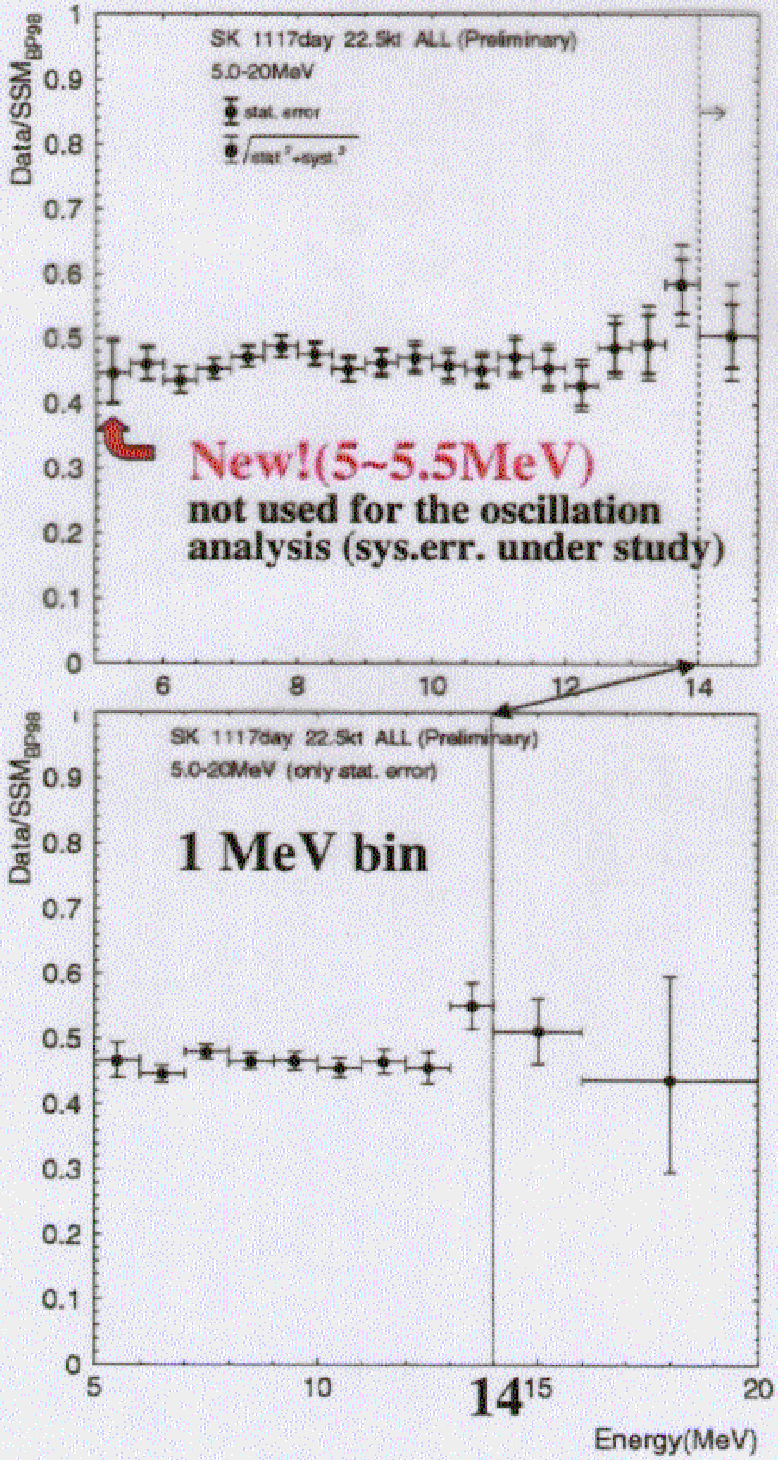
$$\frac{D-N}{(D+N)/2} = -0.034 \pm 0.022 \,{}^{+0.013}_{-0.012} \quad (1.3\sigma)$$

- seasonal variation ~ eccentricity
- no correlation with sunspot number

also SAGE $75.4^{+7.8}_{-7.4}$ SNU (Gavrin

Homestake Cl, I (Lande

Spectrum Ratio to the SSM prediction

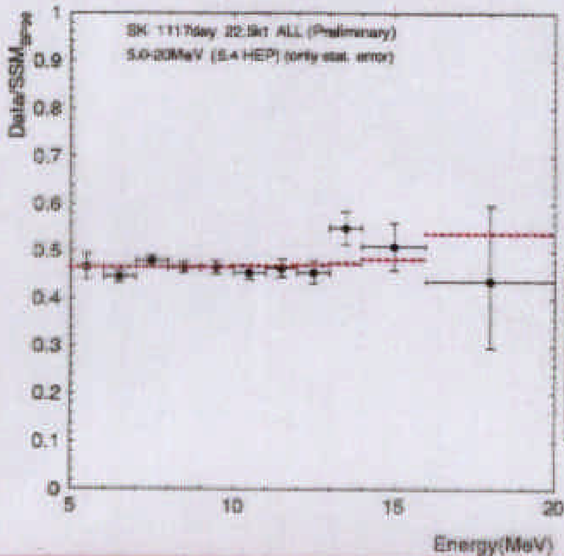


χ^2 for flat :
13.7 / 17dof
(69% C.L.)
incl. sys. err.

Consistent to be flat.

(Suzuki)

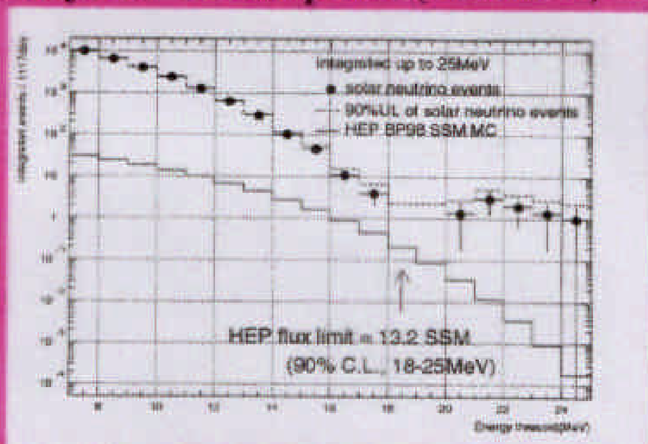
Hep flux



fit: ^{8}B and Hep flux simultaneously

Hep = 5.4±4.5 x SSM Hep

Flux beyond ^{8}B end point (>18MeV)

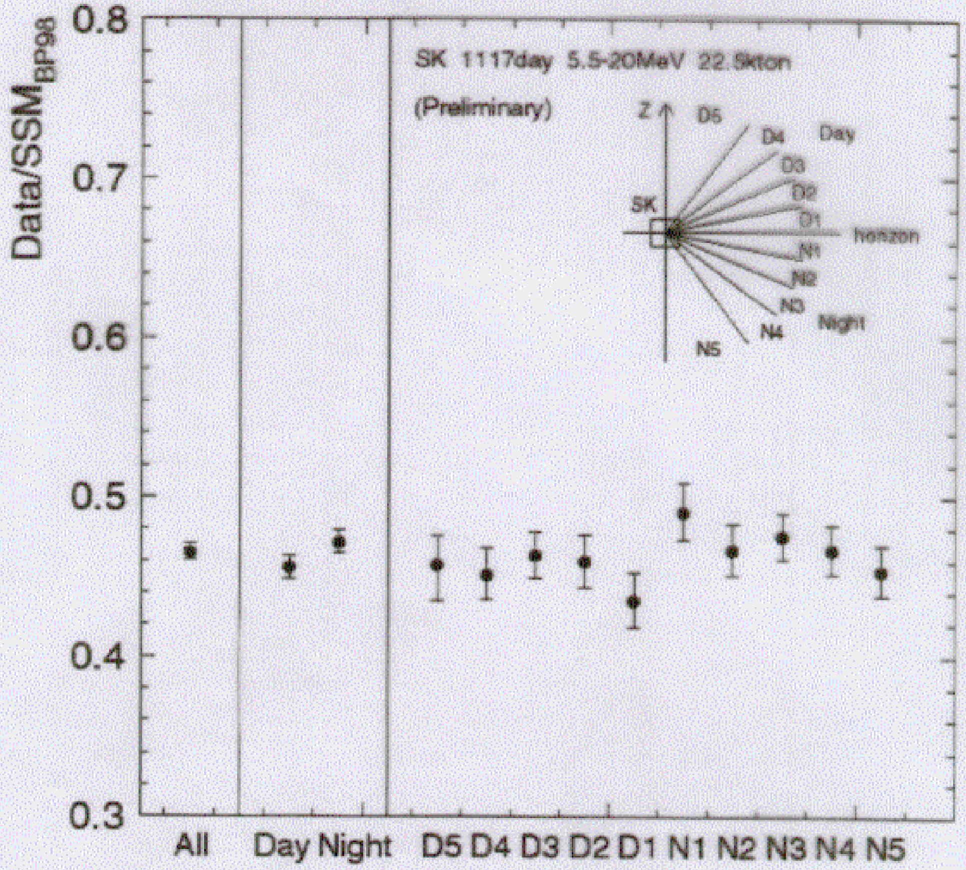


Hep < 13.2 x SSM Hep (quote this number)

Note: effect on the spectrum is very small now

(Suzuki

Day/Night Flux difference



(Suzuki

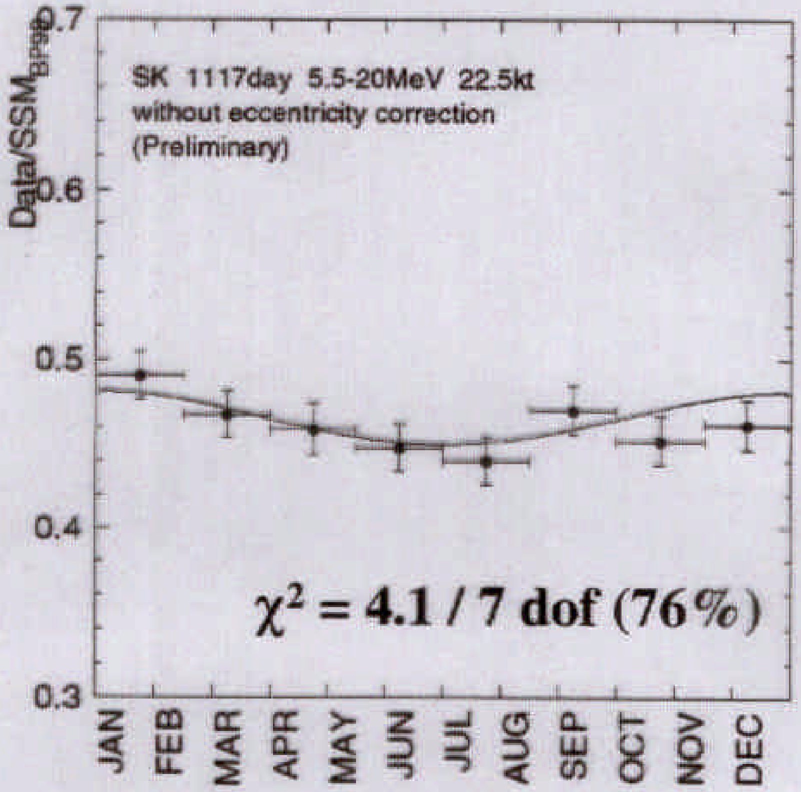
Day = 2.35 ± 0.04(stat.)$\pm^{0.08}_{0.07}$(syst.) x10^6/cm^2/s

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

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

1.3 σ level → not strong yet

Seasonal flux



(Suzuki

Very good agreement with the expected seasonal variation due to the earth's eccentricity

Interpretation

solar model OK
(Turck-Chièze

- problems for VO

  'disfavoured @ 95% c.l.'

(Super-K: Suzuki

- and for SMA

  $dN/dE \leftarrow \sin^2 2\theta \rightarrow D\text{-}N$

  'disfavoured @ 95% c.l.'

$\nu_e \rightarrow \nu_{\mu,\tau}$

favour LMA or LOW

$\Delta m^2 \gtrsim 2\times10^{-5}\,eV^2$

$\nu_e \rightarrow \nu_{sterile}$

'disfavoured @ 95% c.l.'

Indications need confirmation by global analysis

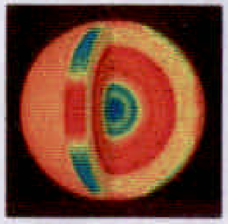
- unified treatment of 'dark side' (Gonzalez-Garcia

  $\Delta m^2 \gtrless 0 \leftrightarrow \theta \lessgtr \pi/4$

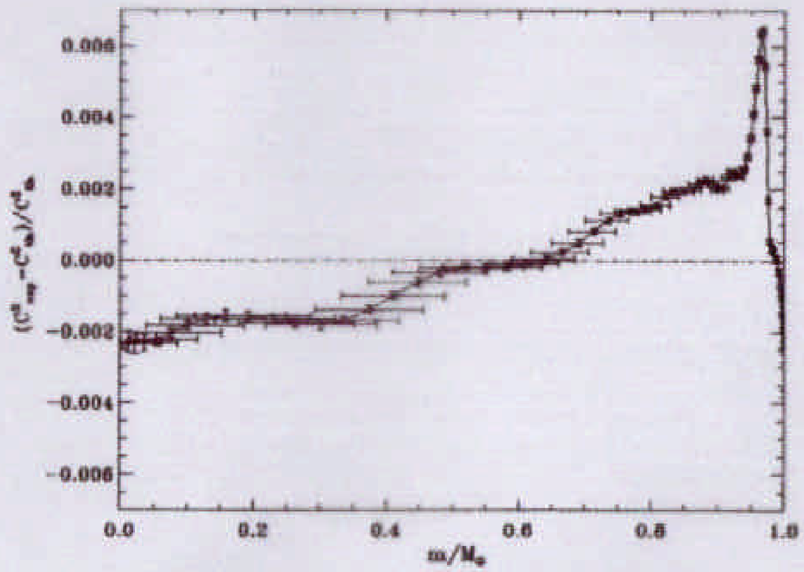
- unified treatment of matter/vacuum effects
- $2 \rightarrow 3 \rightarrow 4$ (?) neutrinos

  where do oscillations $\rightarrow \nu_s$ occur?

(Turck-Chièze



Solar interior shown by acoustic modes

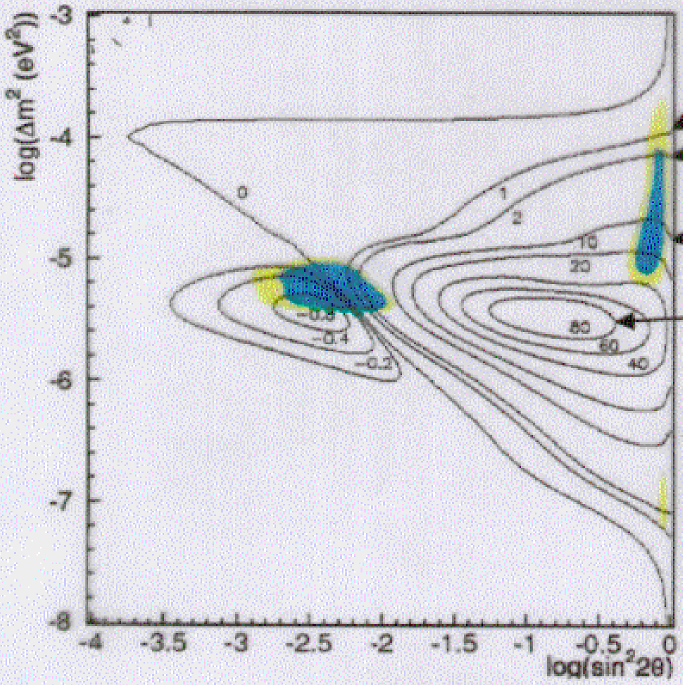


in including low order radial modes

Bertello et al 2000

Garcia, Turck-Chièze, Regulo et al 2000

Expected



1%

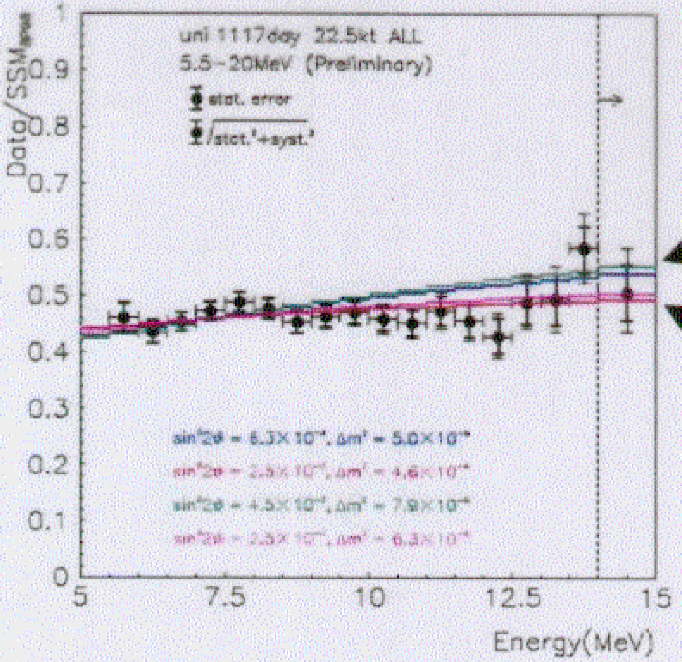
2%

10%

80%

$$\frac{(\text{Night-Day})}{(\text{Night+Day})/2}$$

(Suzuki

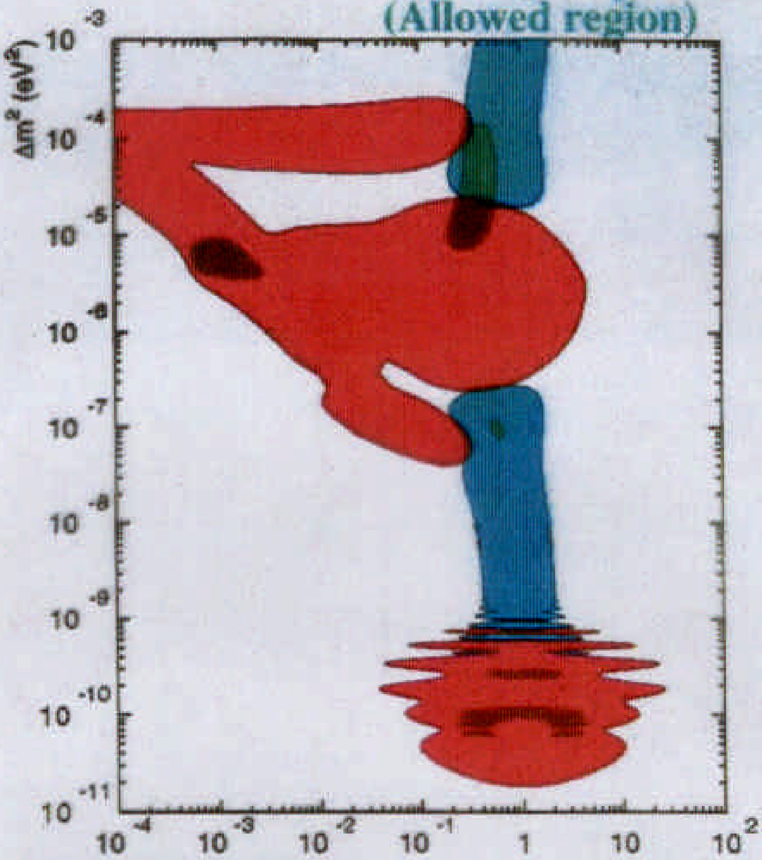


$\sin^2 2\theta =$ $(4.5\text{-}6.3)\times 10^{-3}$

$\sin^2 2\theta =$ 2.5×10^{-3}

$\nu_e \longrightarrow \nu_\mu$ oscillation (95% C.L.)

Super-Kamiokande only
Day/Night Spectrum +flux
(Allowed region)



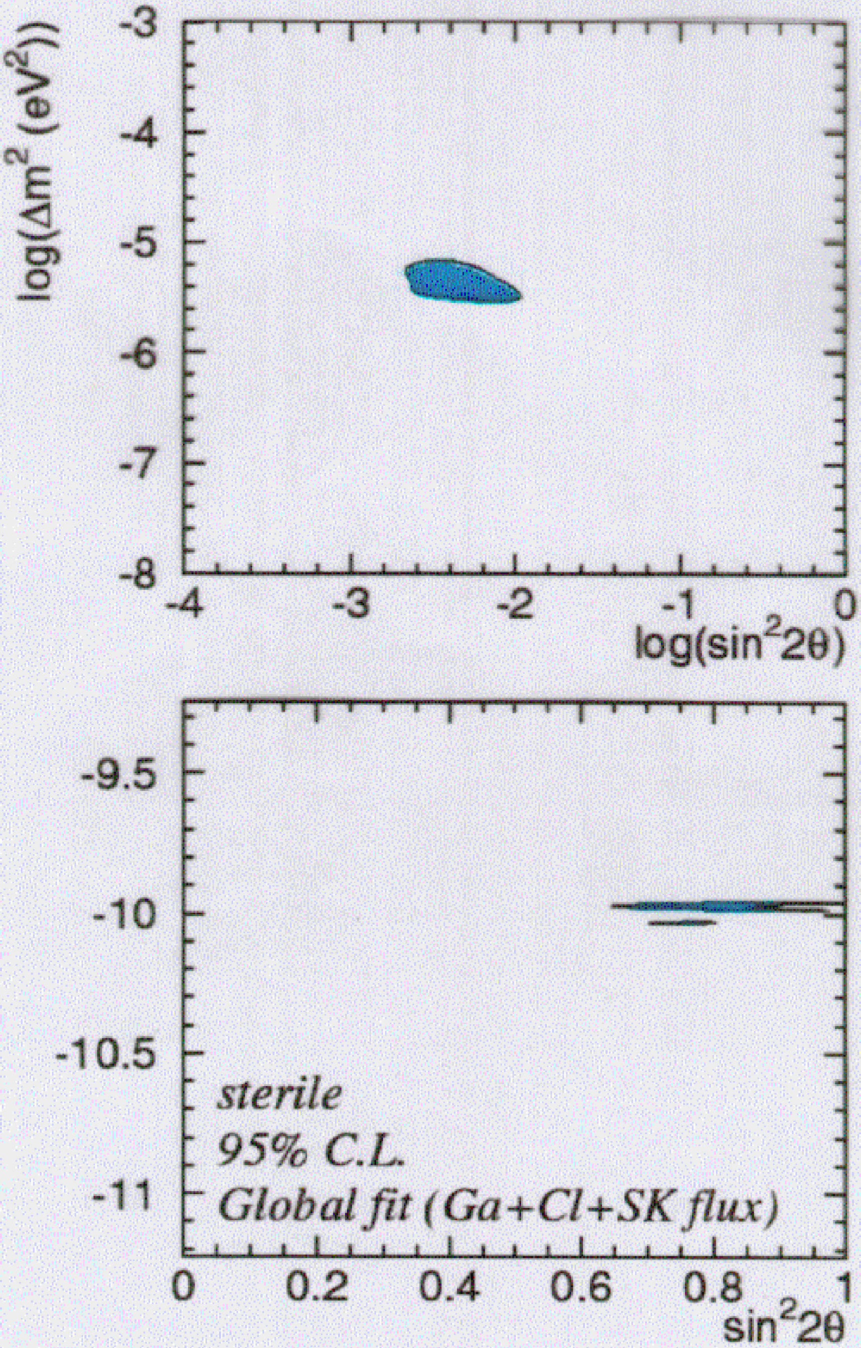
Flux global fit:
Ga+Cl+SKflux
(Allowed region)

Super-Kamiokande only
Day/Night Spectrum
(flux independent)
(Excluded region)

Suzuki

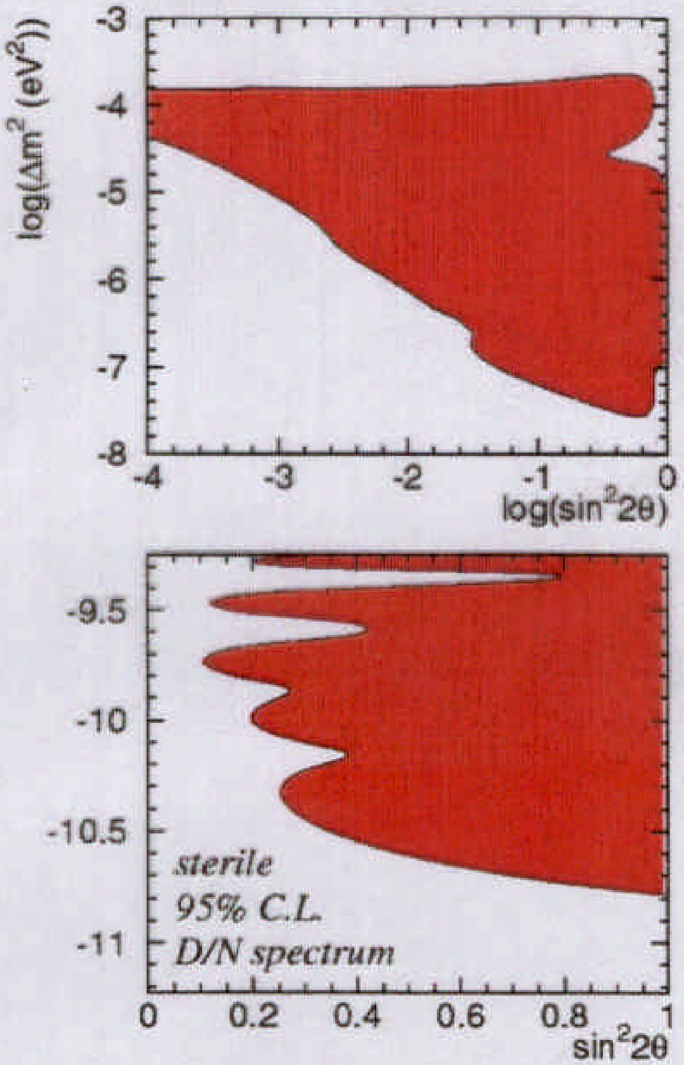
Flux-global (Cl+Ga+SKflux) (Sterile)

Allowed
@95%CL



(Suzuki

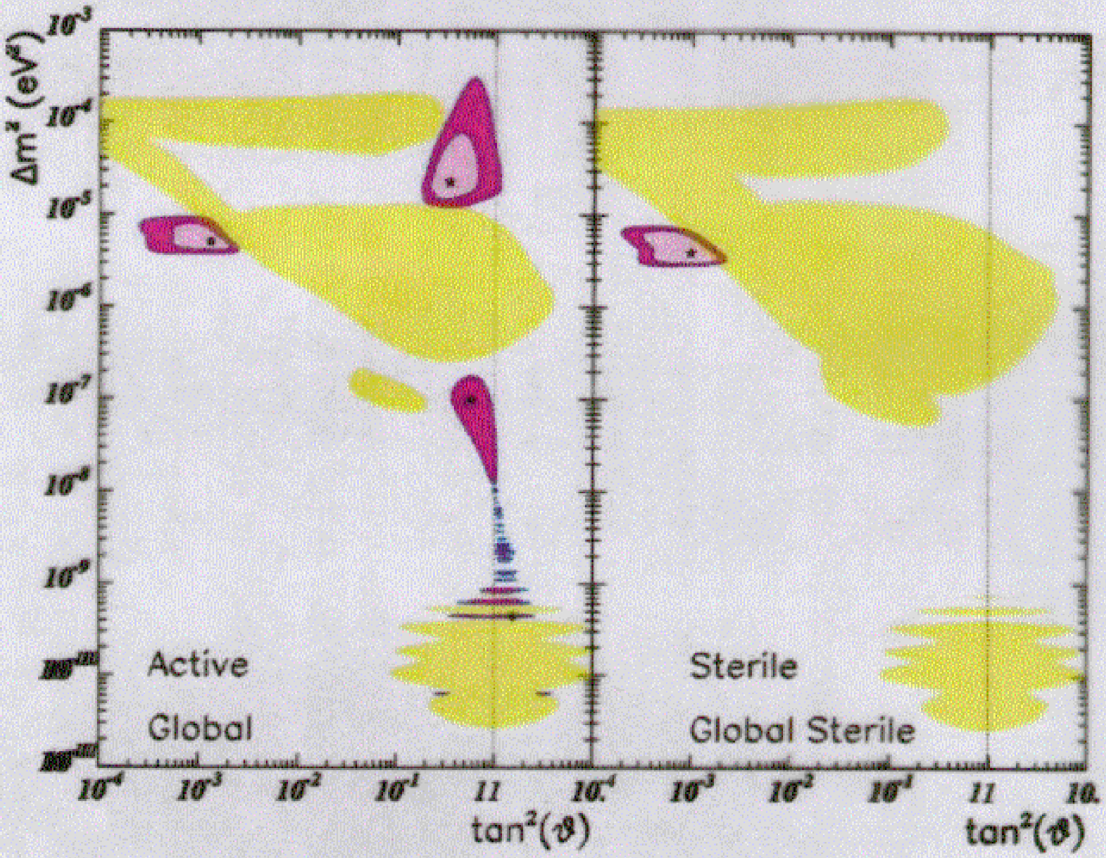
Super-Kamiokande
Day/Night Spectrum (Sterile)



Excluded
@95%CL

Solutions for $\nu_e \to \nu_{active}$ and $\nu_e \to \nu_{sterile}$

Gonzalez-Garcia



– Why differences for oscillations into active or sterile?
Main effect is different contribution to event rates in SuperK

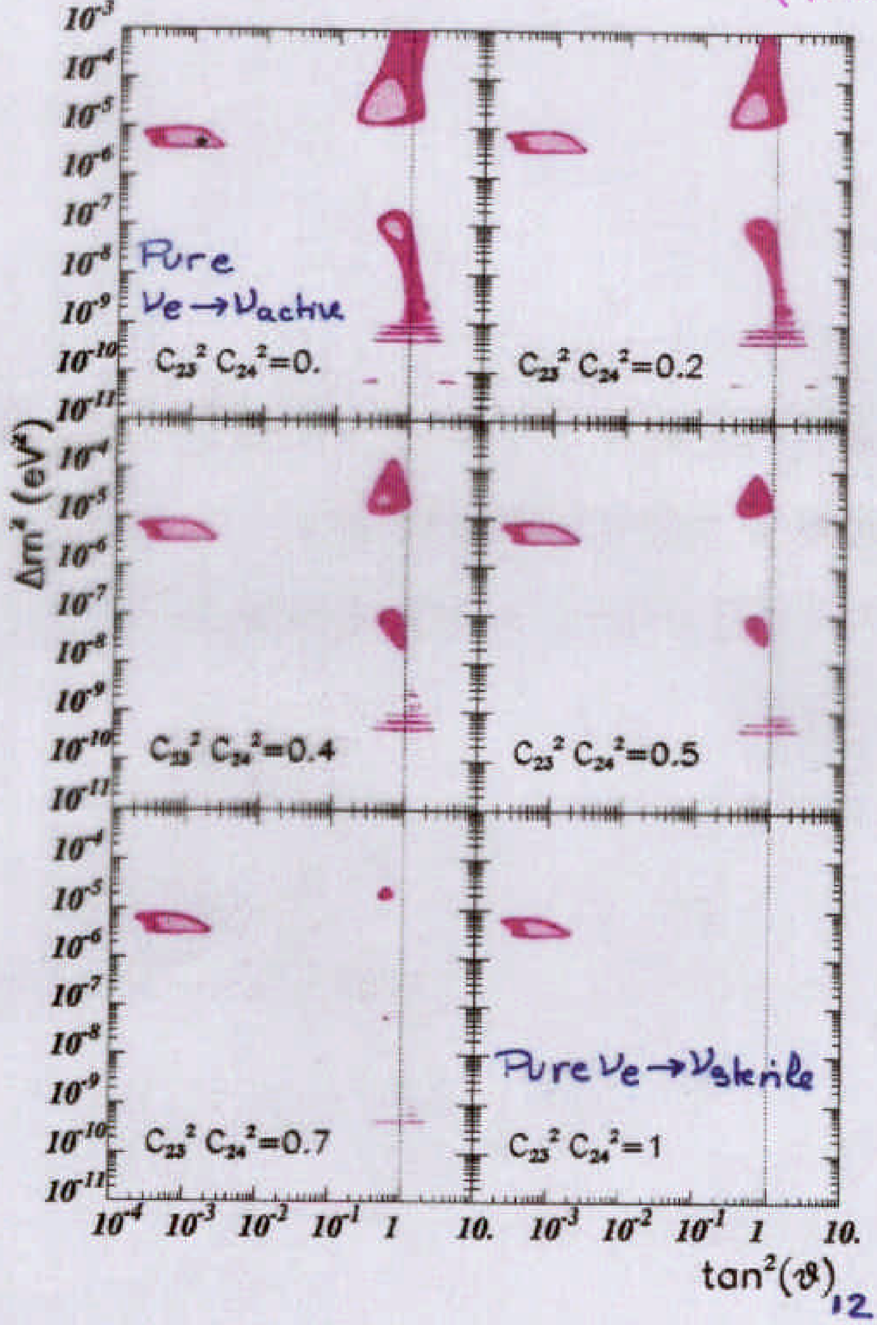
$\nu_{\mu(\tau)} + e \to \nu_{\mu(\tau)} + e \to$ NC events in SuperK
$\nu_s + e \not\to \nu_s + e \to$ no NC events in SuperK

Also slightly different survival probabilities in the sun

Gonzalez - 20

Solutions for Four-neutrino Oscillations

(Gonzalez-Garcia



- **LMA, LOW and VAC solutions can have a subdominant $\nu_e \to \nu_s$ component**

Emerging Default Option

- Three light neutrinos
- Hierarchical masses
- ~ Bimaximal mixing

$$U_{MNS} \simeq \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

- Majorana masses
- small dipole moments
- long lifetimes

(Kayser

X Questions

rule out ν_s?

degenerate?
inverse hierarchy?

size of θ_{13}
rule out SMA?
VO or LMA or LOW?
CP violation?
$\beta\beta$ decay?

Sun? laboratory?

cosmology, LBL?

How do we PROVE that $m_\nu \neq 0$?

5- Future Solar Neutrino Experiments

- Data disfavour many oscillation scenarios

SMA, VO, $\nu_e \to \nu_{sterile}$, ...

But no 'smoking gun' yet

no spectral distortion

no day-night effect

seasonal effect ~ eccentricity

- Opportunity for SNO, BOREXINO, KamLAND
(Ranucci (Piepke

$\uparrow$ disentangle NC, CC @ 'high' E

Need for new generation of 'low' E experiments
(von Feilitzsch

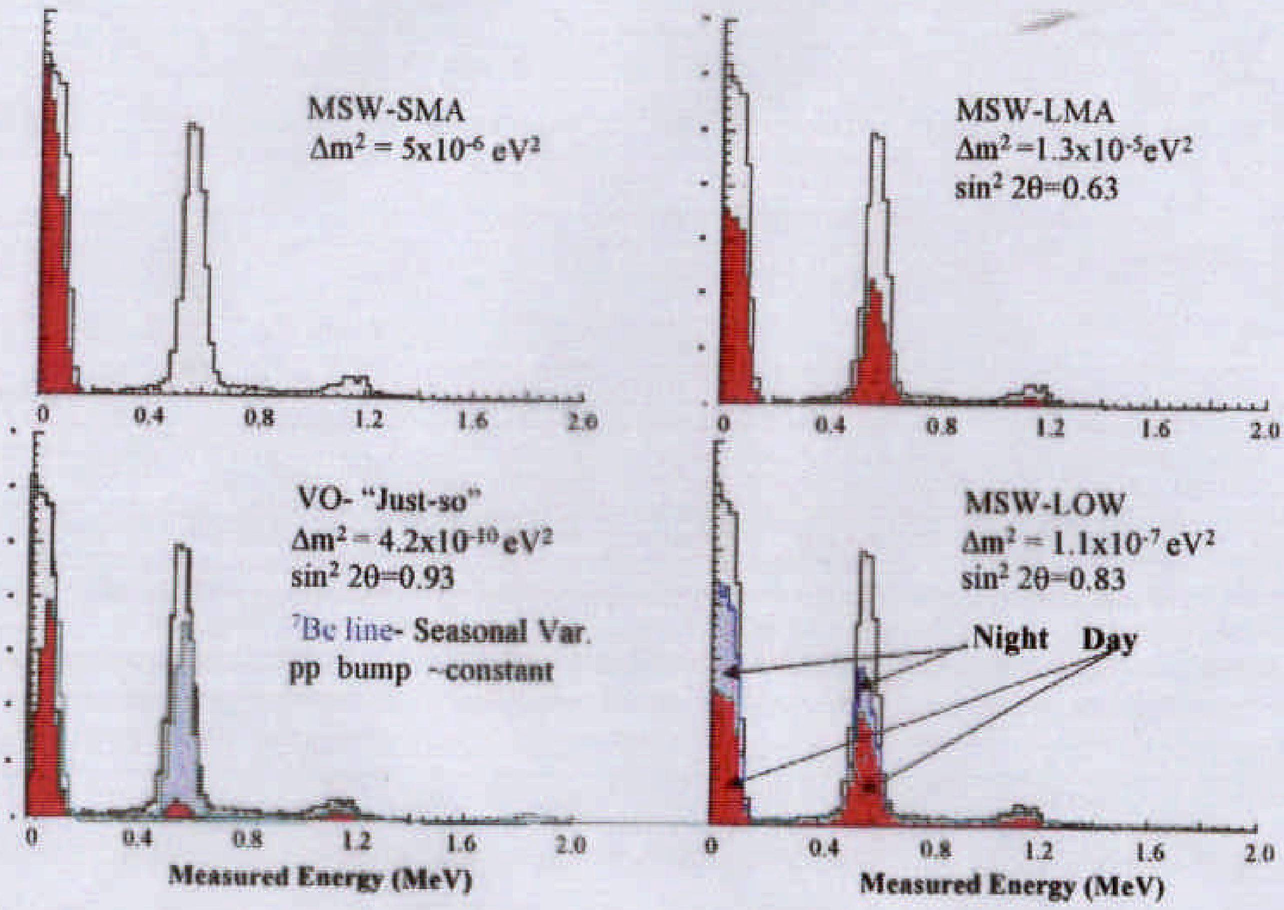
energy spectrum, NC/CC

$\downarrow$

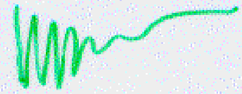
e.g. LENS

Response of Yb-LENS to Neutrino Flavour Conversion Scenarios

(von Feilitzsch



Long-Baseline Experiments

needed to convince sceptics? 

enable precision measurements Δm^2_{23}, $\sin^2 2\theta_{23}$

make different measurements possible $\nu_\mu \to \nu_\tau$

K2K

a triumphant start! (Nakamura

$\sim 2 \times 10^{19}$ p.o.t. $(\to 10^{20})$

beam monitor ~ Monte Carlo

events seen w/o background in Super-K

sensitive to 'interesting' range of Δm^2

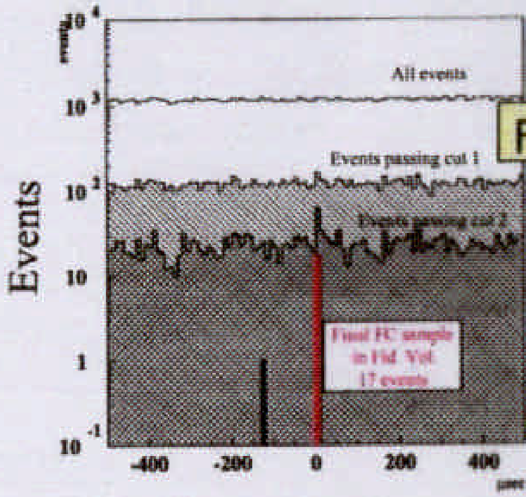
promising deficit of events

but beware tricks of low statistics!

more data eagerly awaited

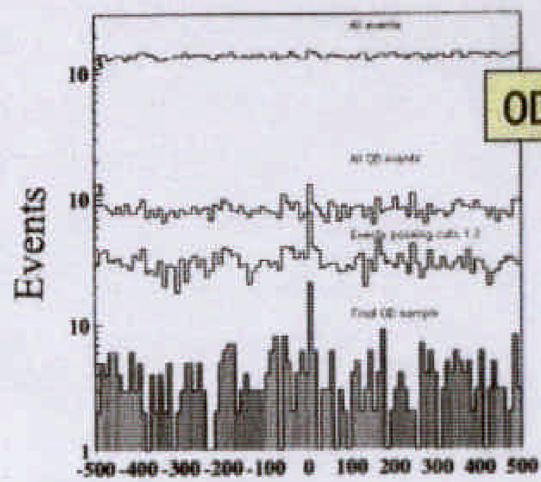
+ energy spectrum
+ π^0 production in near detector

Time difference distributions



FC candidates

Cut 1: High energy trigger
Good KEK beam spill
Cut 2: 200 < p.e. < 50,000
Remove flasher events
Cut 3: No significant OD activity
Fiducial cut



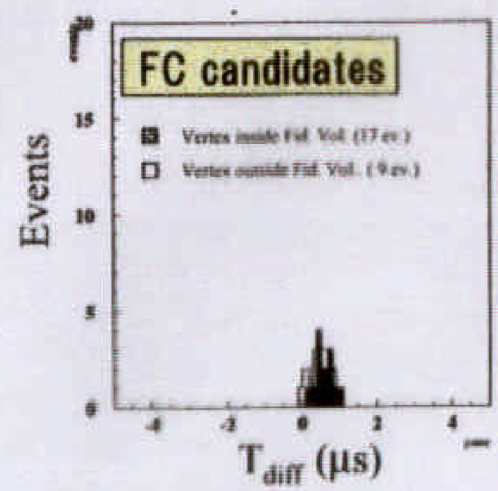
OD candidates

SK Events

$$-0.2 \le T_{Diff} \equiv T_{SK} - T_{Spill} - \mathrm{TOF} \le 1.3\ \mu\mathrm{sec}$$

T_{Spill}, T_{SK}: Abs. time of spill start, SK event measured with GPS
TOF: Time of flight of neutrino from KEK to Kamioka
GPS: Global Positioning System

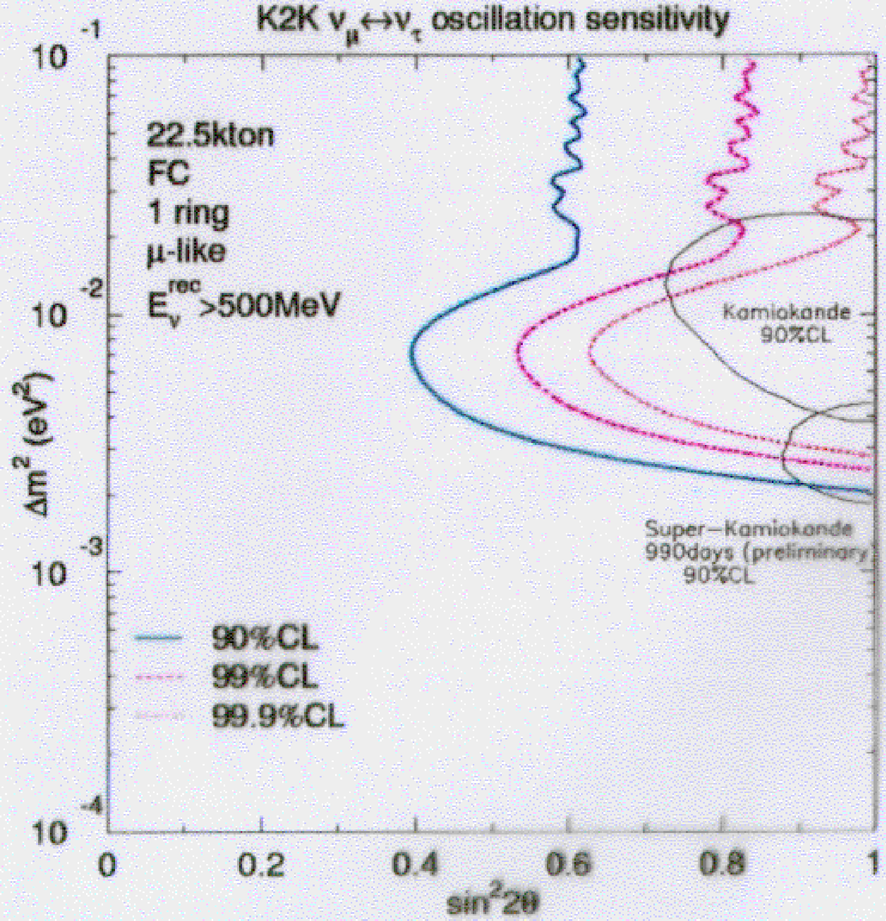
(Nakamura



FC candidates

prospective sensitivity

(Nakamura



Naka - 04

SK observed vs. expected

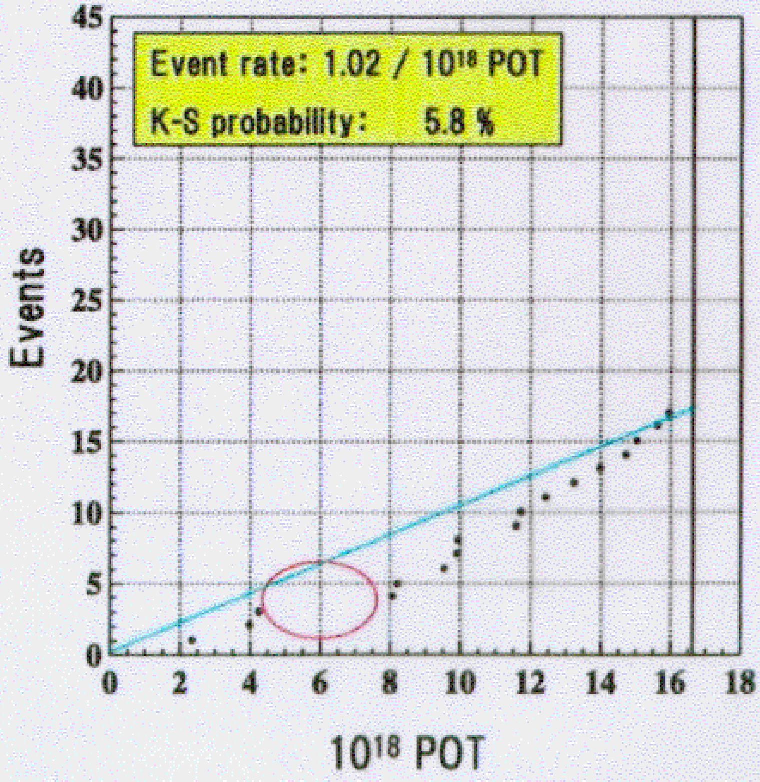
(Nakamura

			Expected		
			$\Delta m^2 (\times 10^{-3} eV^2)$		$\sin^2 2\theta = 1$
	Obs.	Null Osc.	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
	Σ = 44	73.8	49.8	33.1	26.9

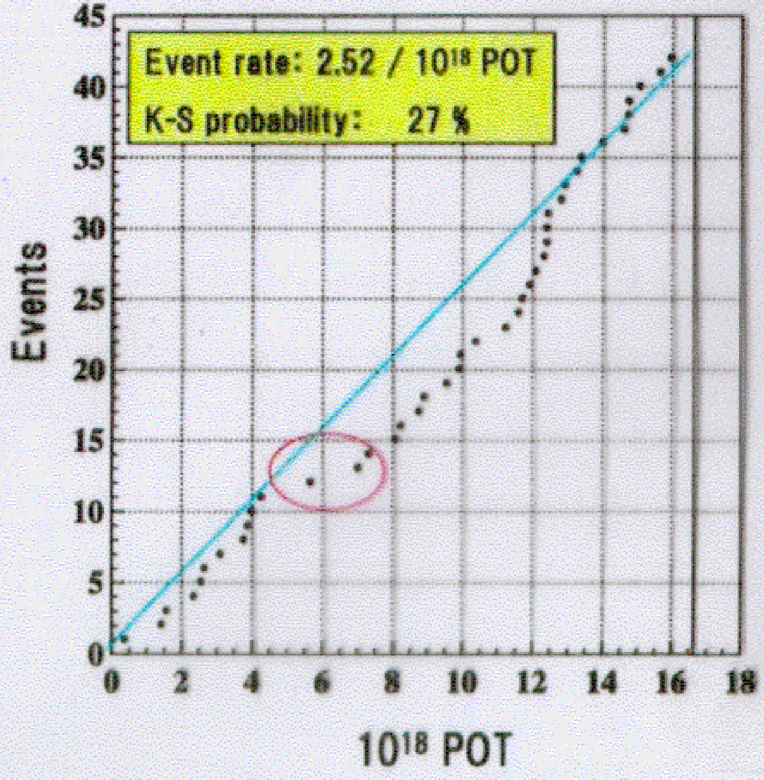
Events vs no. of protons on target

(Nakamura

FC events in 22.5 kton fiducial volume



All events (FC + OD)

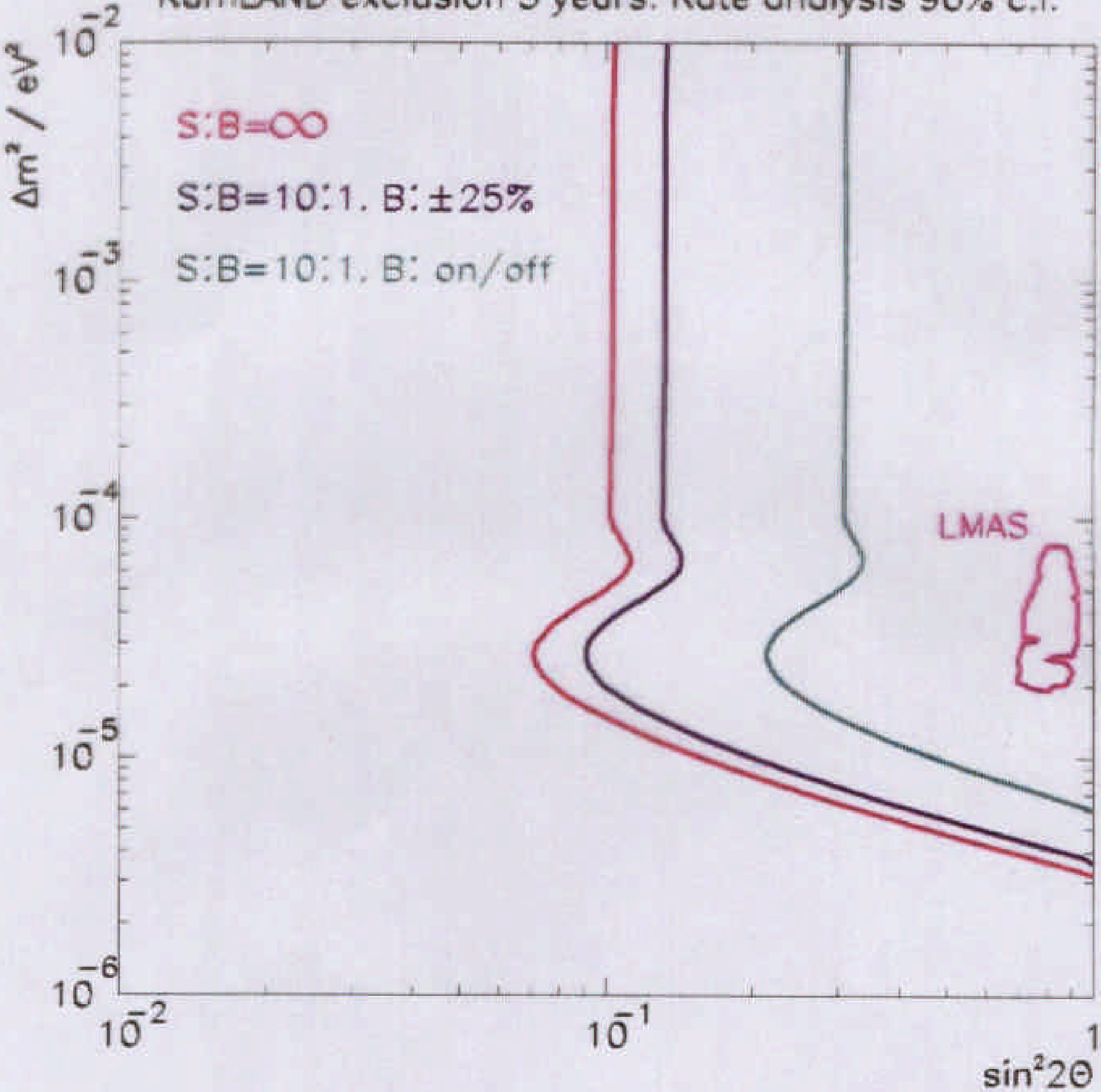


Naka - 14

KamLAND

definitive test of LMA solar solution

KamLAND exclusion 3 years. Rate analysis 90% c.l.



(Piepke

+ solar neutrinos:

D-N asymmetry for ^7Be

seasonal variation

MINOS

(Wojcicki

construction underway

ν_μ disappearance

see oscillation pattern

measure Δm^2_{23}, $\sin^2 2\theta_{23}$

good sensitivity to $\sin^2 2\theta_{13}$

discrimination: $\nu_\mu \to \nu_\tau$ vs $\nu_\mu \to \nu_s$

hope no financial delays

CERN - Gran Sasso

(Rubbia

beam approved end 1999

primary objective $\nu_\mu \to \nu_\tau$: τ observation

can cover Super-K region CHORUS, NOMAD, DONUT
(Ludovici (Mezzetto (Lundberg

good sensitivity to $\sin^2 2\theta_{13}$

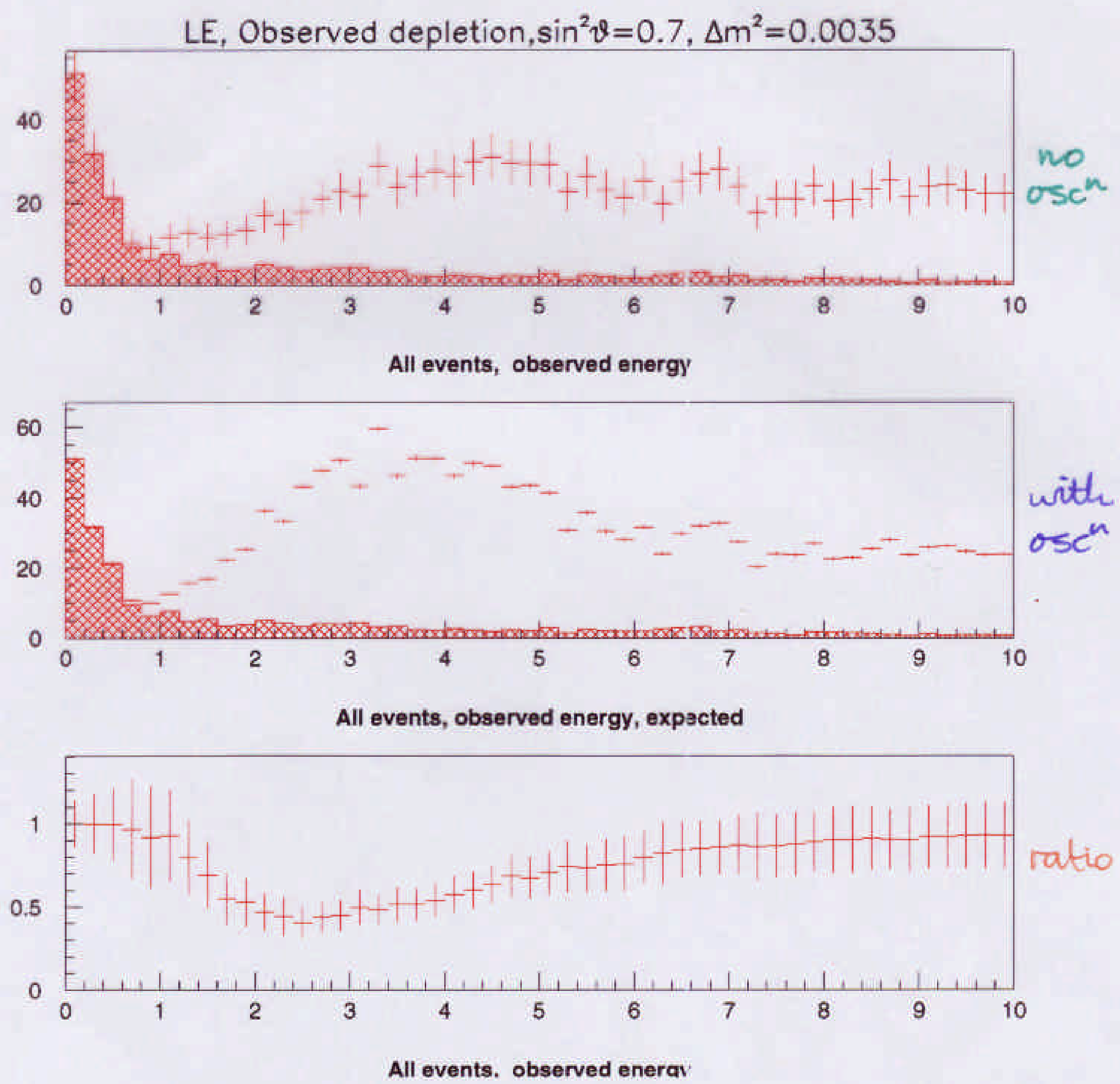
OPERA to be discussed in 2000

ICANOE making module test

MONOLITH could use beam for oscillations

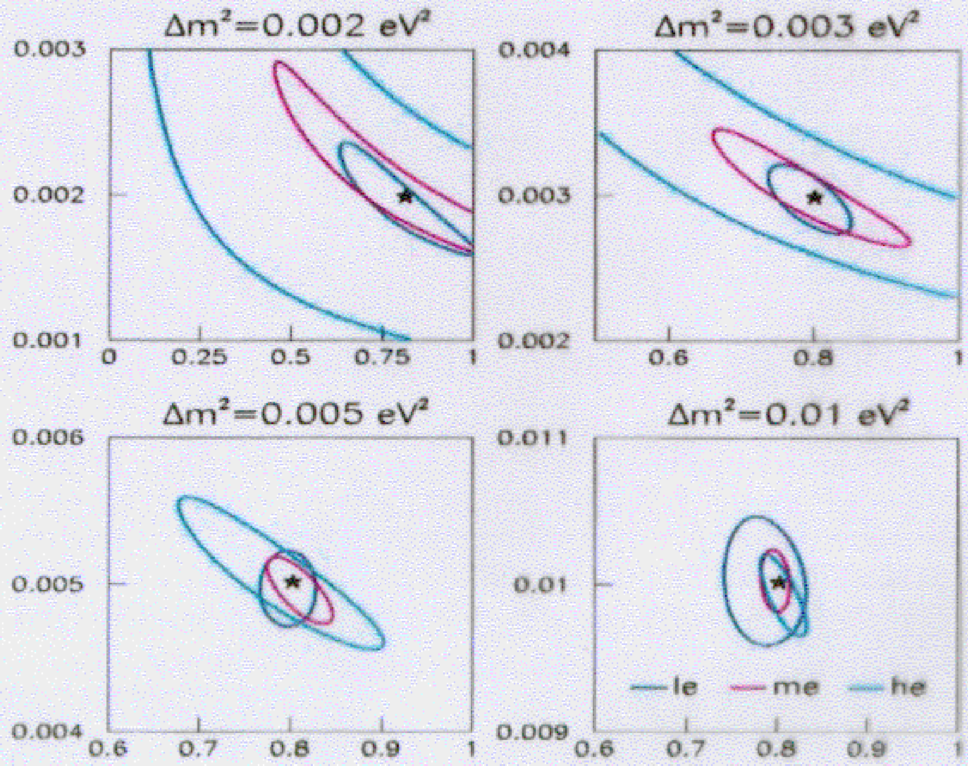
CC Oscillation Pattern in MINOS

(Wojcicki



Comparison of Different Beams

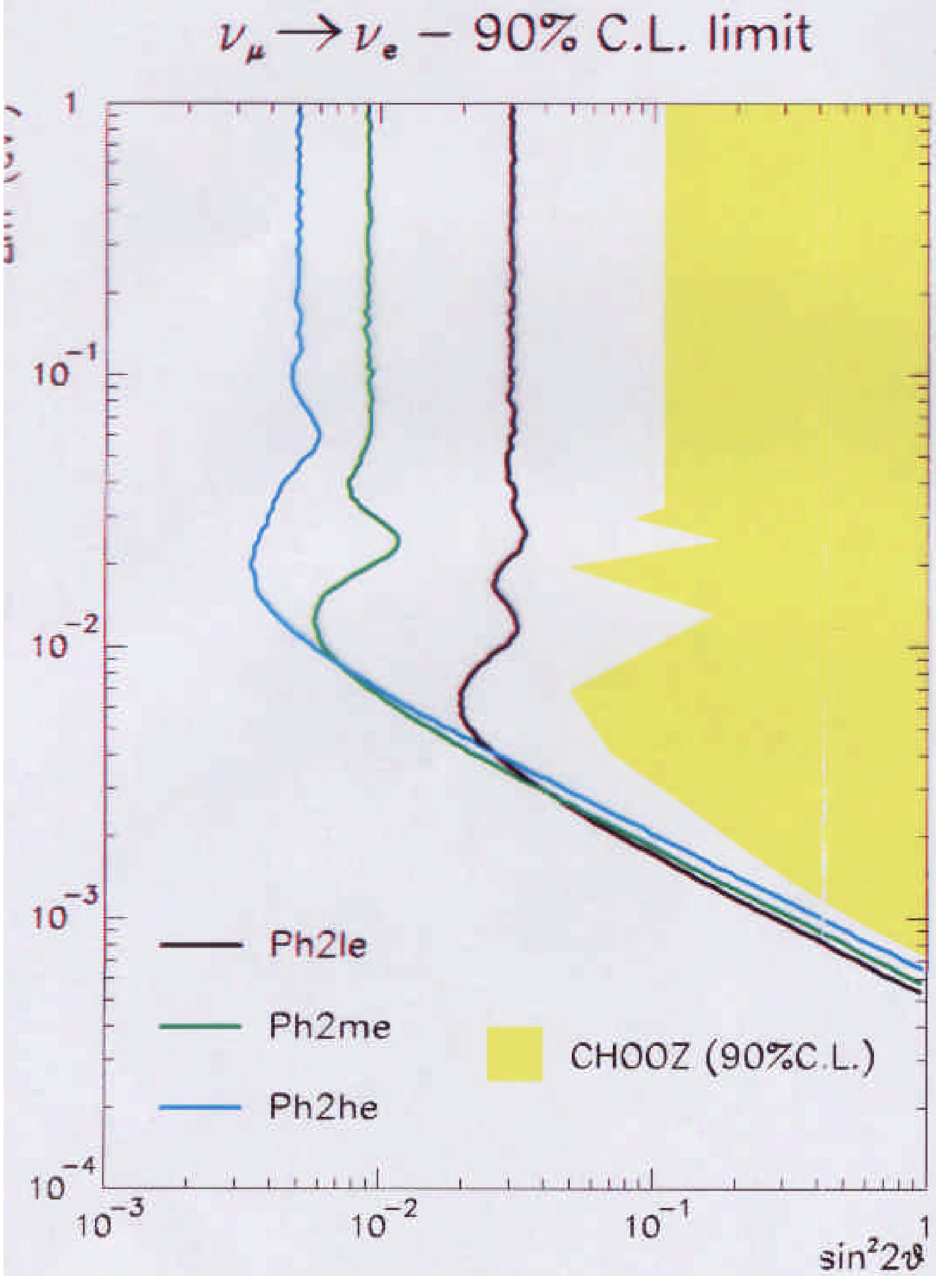
(Wojcicki



CC Energy Spectru
68% Contours
10kt-yr exposure

MINOS Physics Reach for $\nu_\mu \to \nu_e$

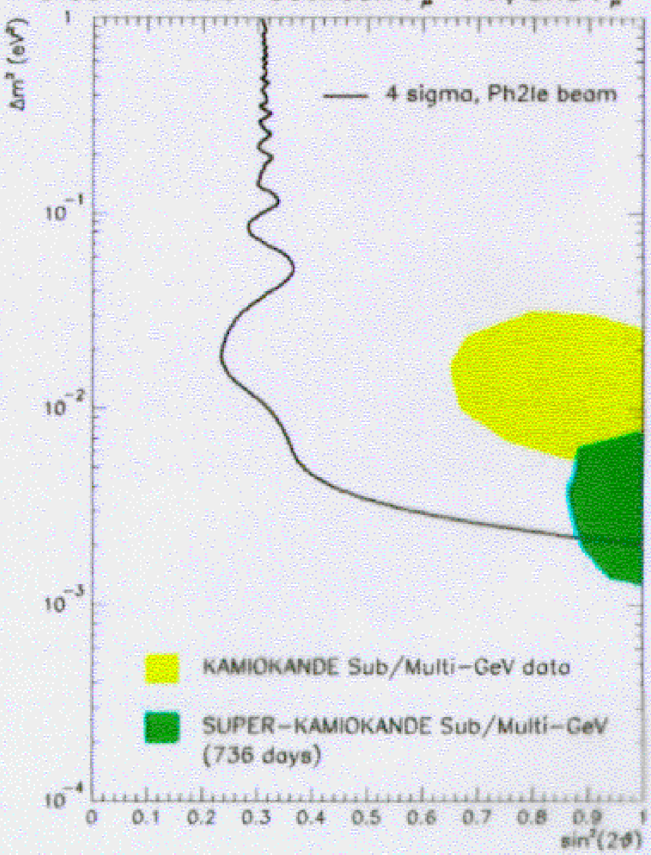
(Wojcicki



MINOS Oscillation Mode Sensitivity

(Wojcicki

Discrimination between $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$



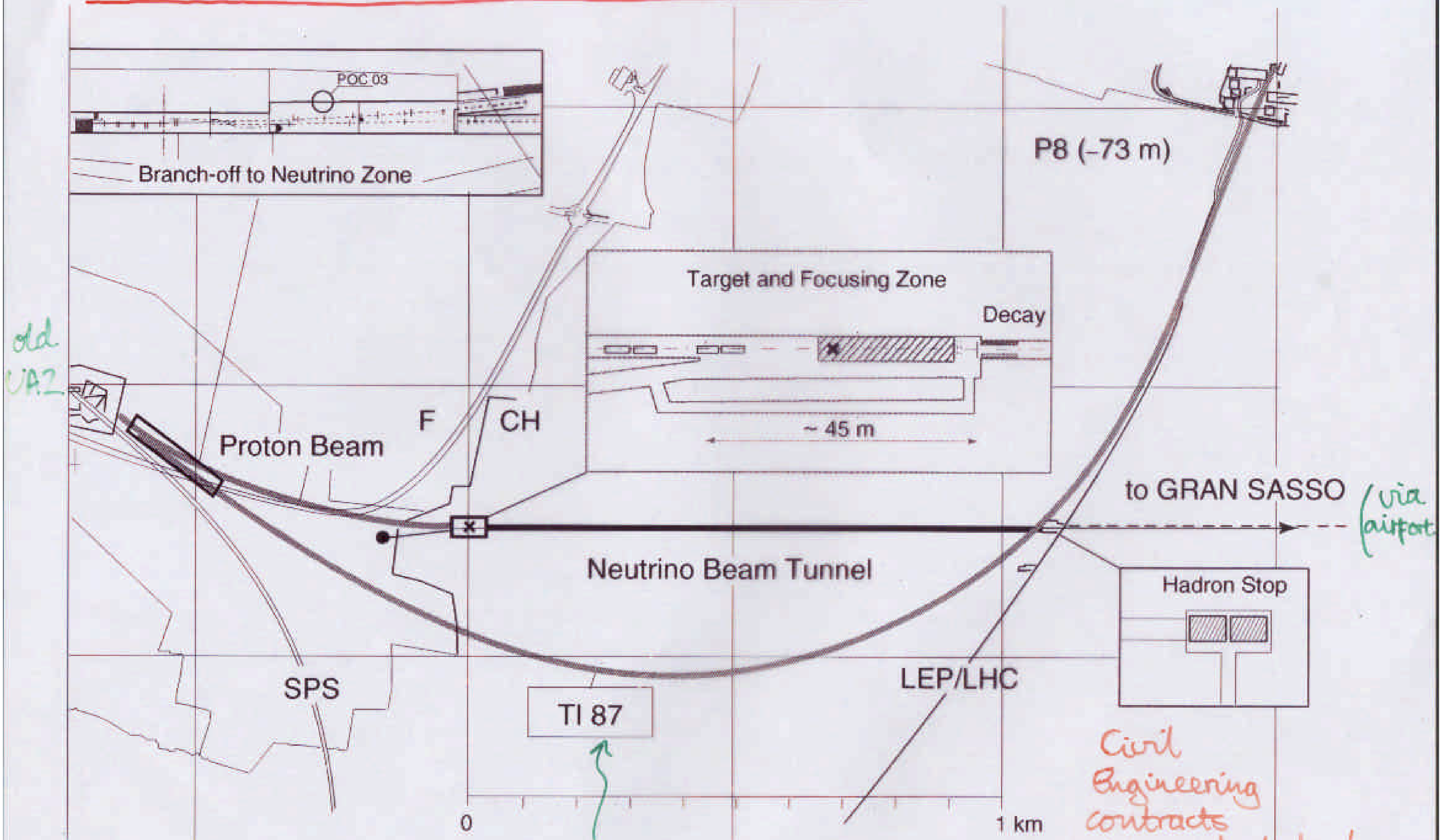
From T test measurement

(NC-like/CC-like ratio)

10 kt yr exposure

Determination of oscillation mode from the T test becomes more difficult at low Δm^2

Possible CERN Long-Baseline Beam



Civil Engineering contracts approved today!
~2/3 total

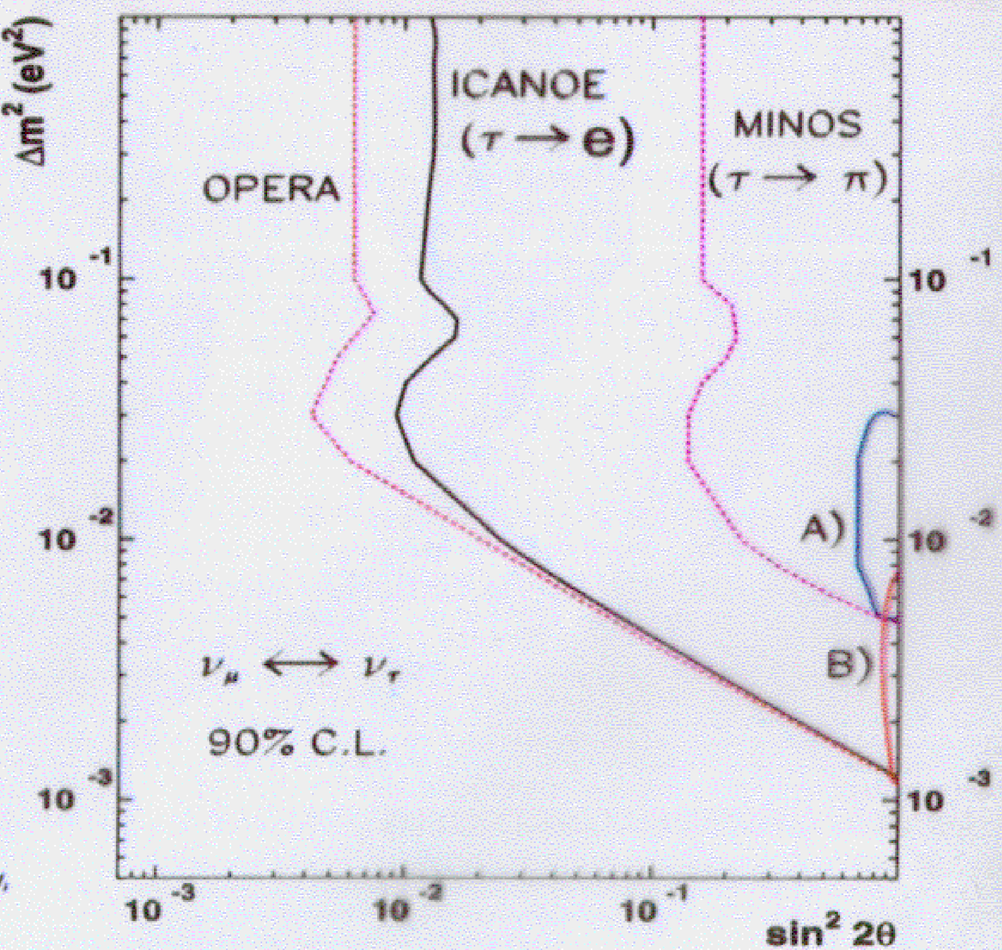
SPS → LHC transfer: new design for beam line using normal magnets

(CHORUS: Ludovici) (NOMAD: Mezzetto) (Rubbia

Two-family $\nu_\mu \to \nu_\tau$ oscillations: sensitivity

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

4 years



(MINOS high energy beam (PH2high) configuration, NUMI-L228 & TDR)
(OPERA, CERN/SPSC 99-20)
(ICANOE, tau appearance, electron channel only, optimized for low Δm^2)

(Lundberg

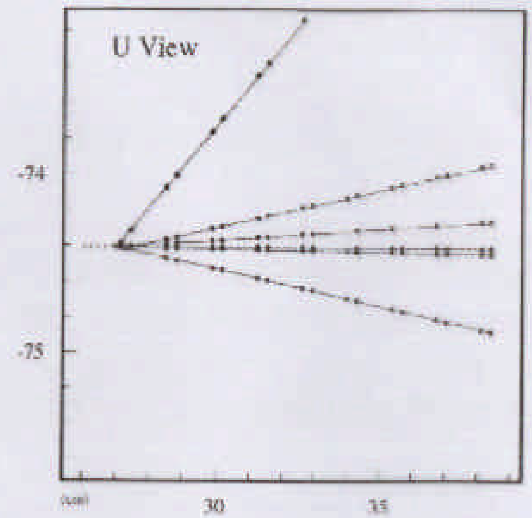
DONUT

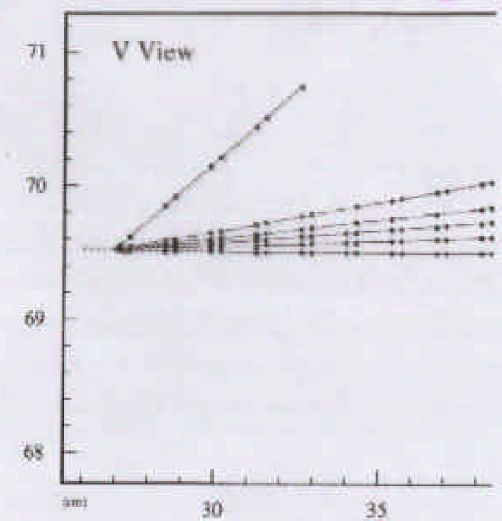
Fermilab E-872

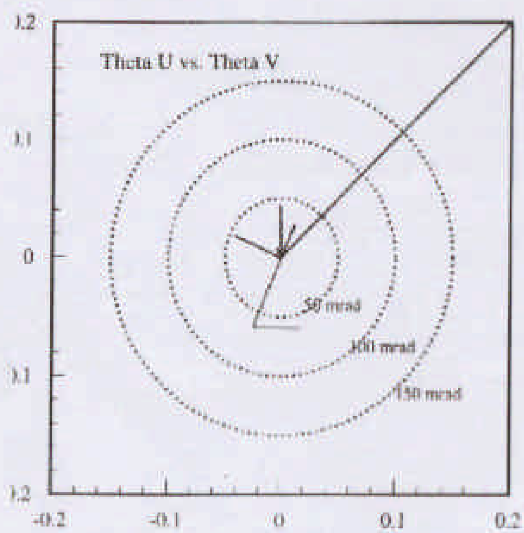
Run= 3039 Event= 1910

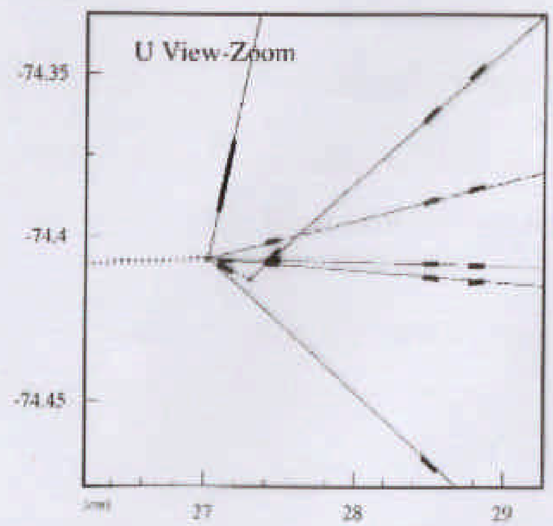
Tau Candidate

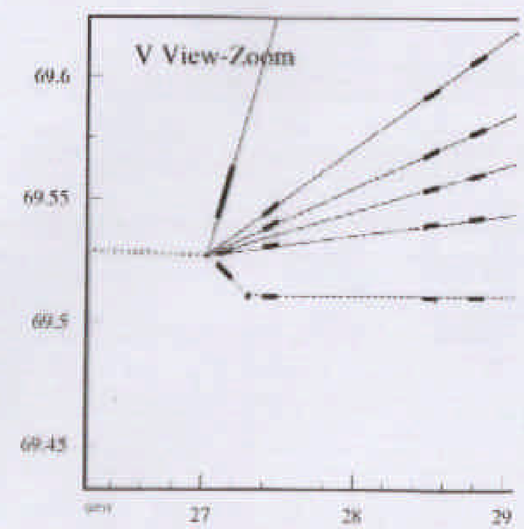
S Decay
Tau - hadron
Flight Length : 270 microns
Kink Angle : 88 mrad







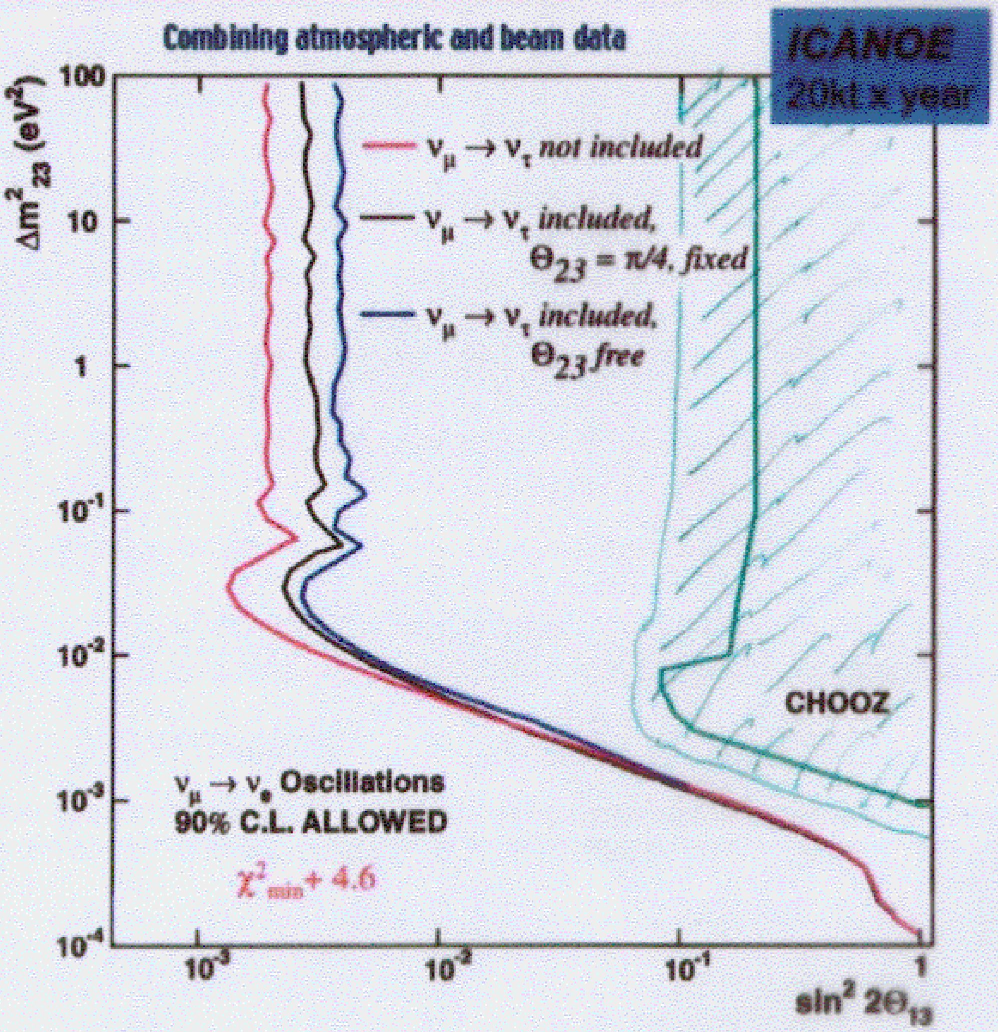




Lund- - 32

(Rubbia

Sensitivity to θ_{13} in three family-mixing

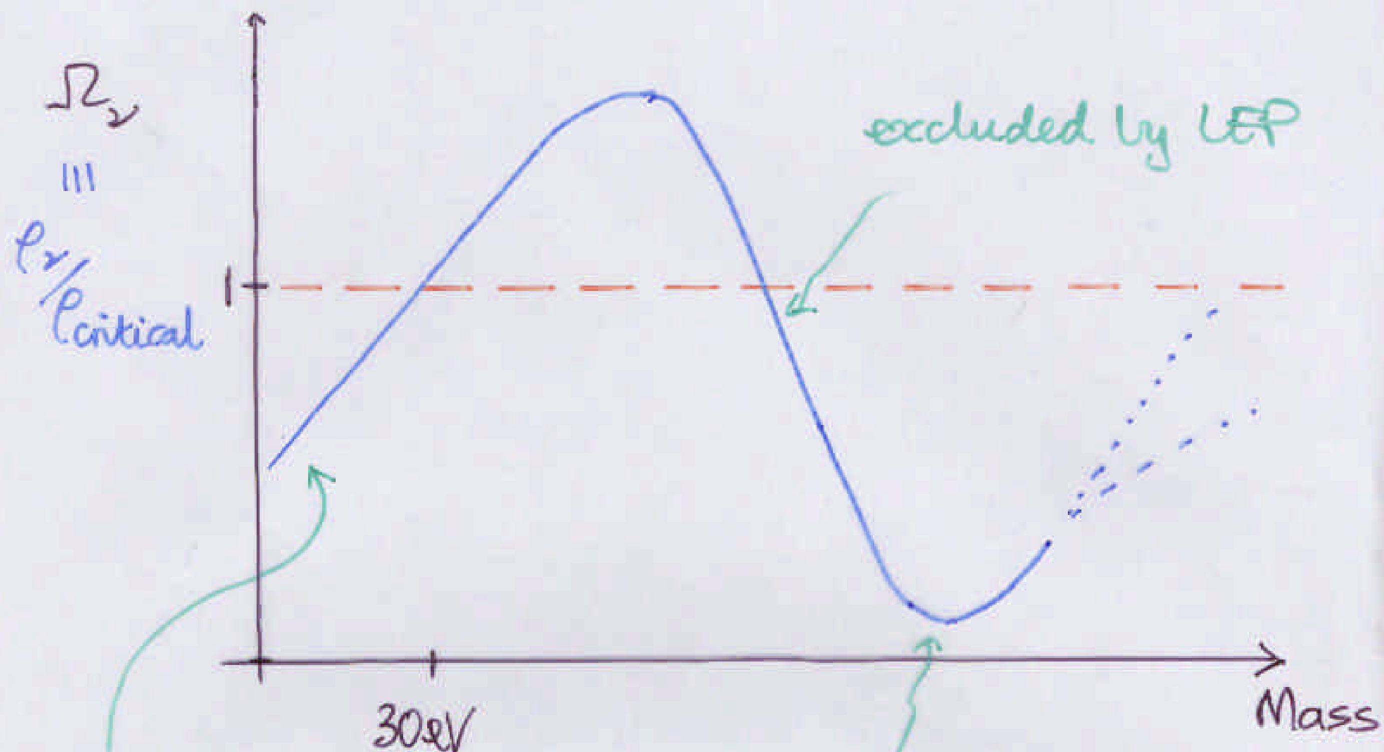


- Limit slightly degraded by inclusion of tau events and leaving contribution as free parameter
- Improved if θ_{23} fixed (e.g. to 45° or from other experiments)
- Almost two-orders of magnitude improvement over existing limit

Rubbia-44

6 - Relic Mass Density

of neutrino or similar ...



n_ν independent of mass

$\Rightarrow \rho_\nu \propto m_\nu$

efficient annihilation via Z

Three generic regions where $\Omega_\nu \sim 1$

$m_\nu \sim 30$ eV $\Downarrow$ Hot Dark Matter

$m_\nu \sim$ few GeV, excluded by LEP for ν

$\gtrsim 100$ GeV $\Downarrow$ Cold Dark Matter

supersymmetric relics

Density Budget of the Universe

we know they exist, we know they weigh

Baryons $\Omega_b \sim 0.05$ (Tegmark, Bond

fantastic concordance: BBN $\simeq$ CMB

we know they exist, probably they weigh

Neutrinos $\Omega_{hot} \lesssim 0.1$

$m_\nu \lesssim 3\,eV$

if they exist, they certainly weigh

Cold Dark Matter $\Omega_{cold} \sim 0.3$ good for structures (Navarro

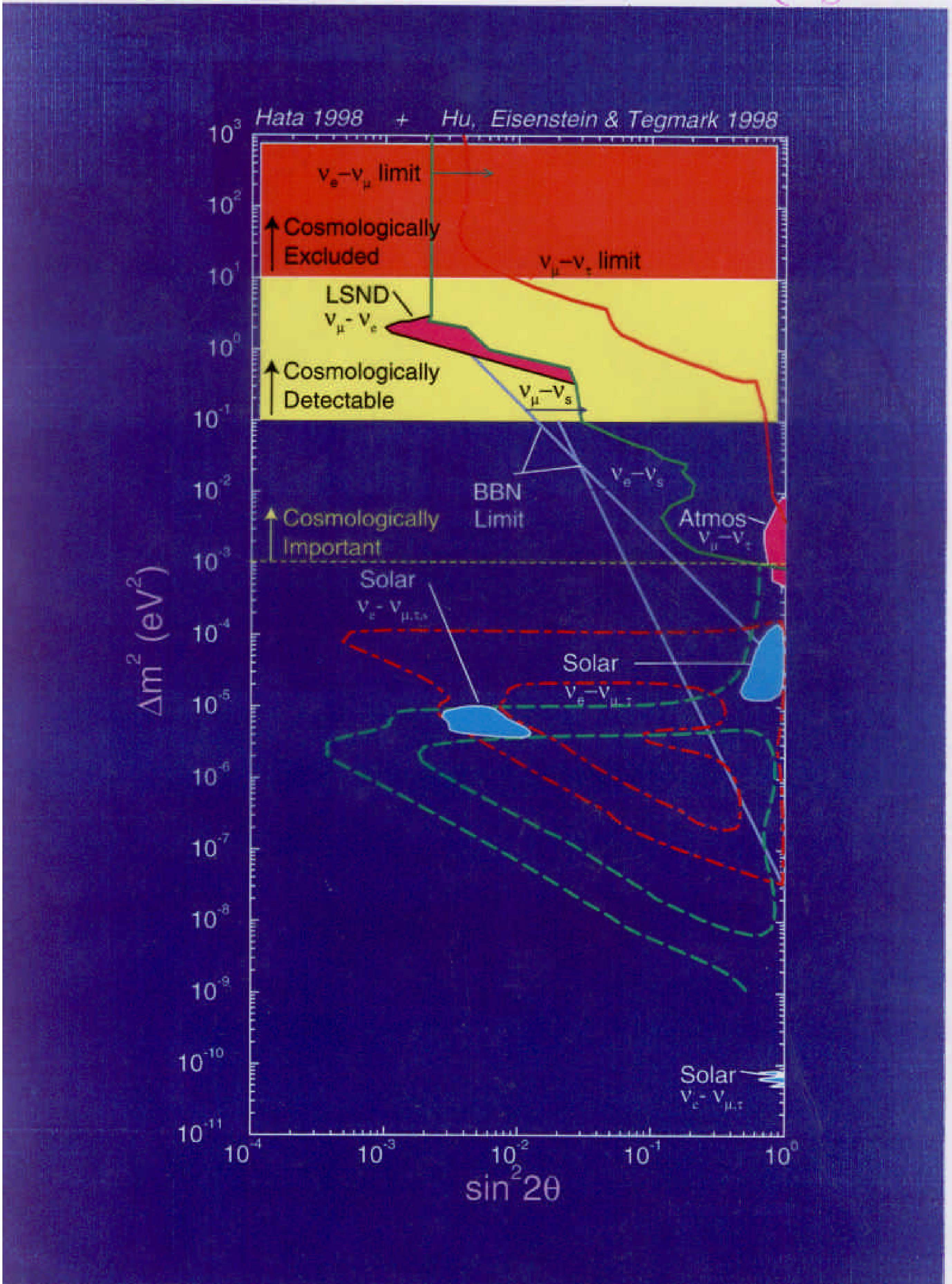
axions or supersymmetric particles or ?

van Bibber) (Akerib, Bernabei, Gondolo

Dark Energy $\Omega_\Lambda \sim 0.65$ (Turner

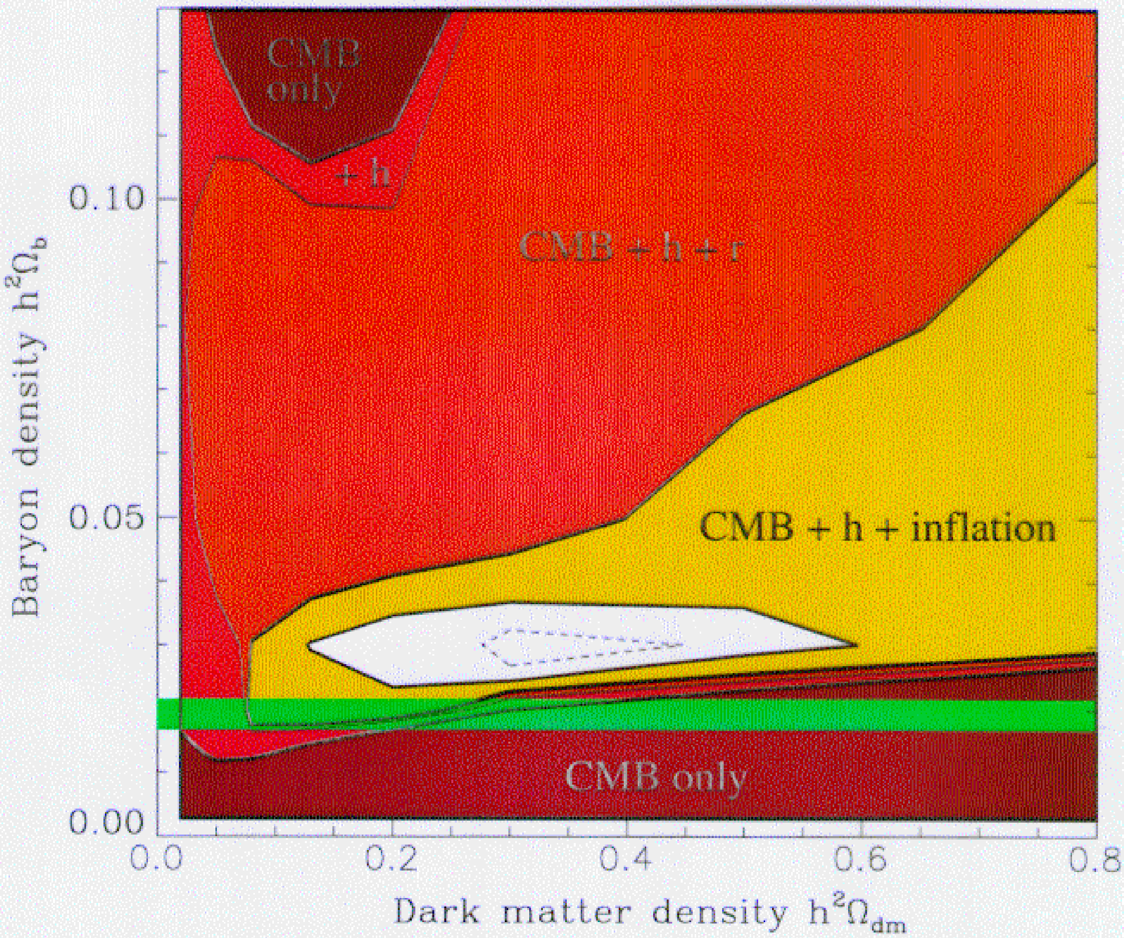
concordance: large-scale structure, CMB, SNae

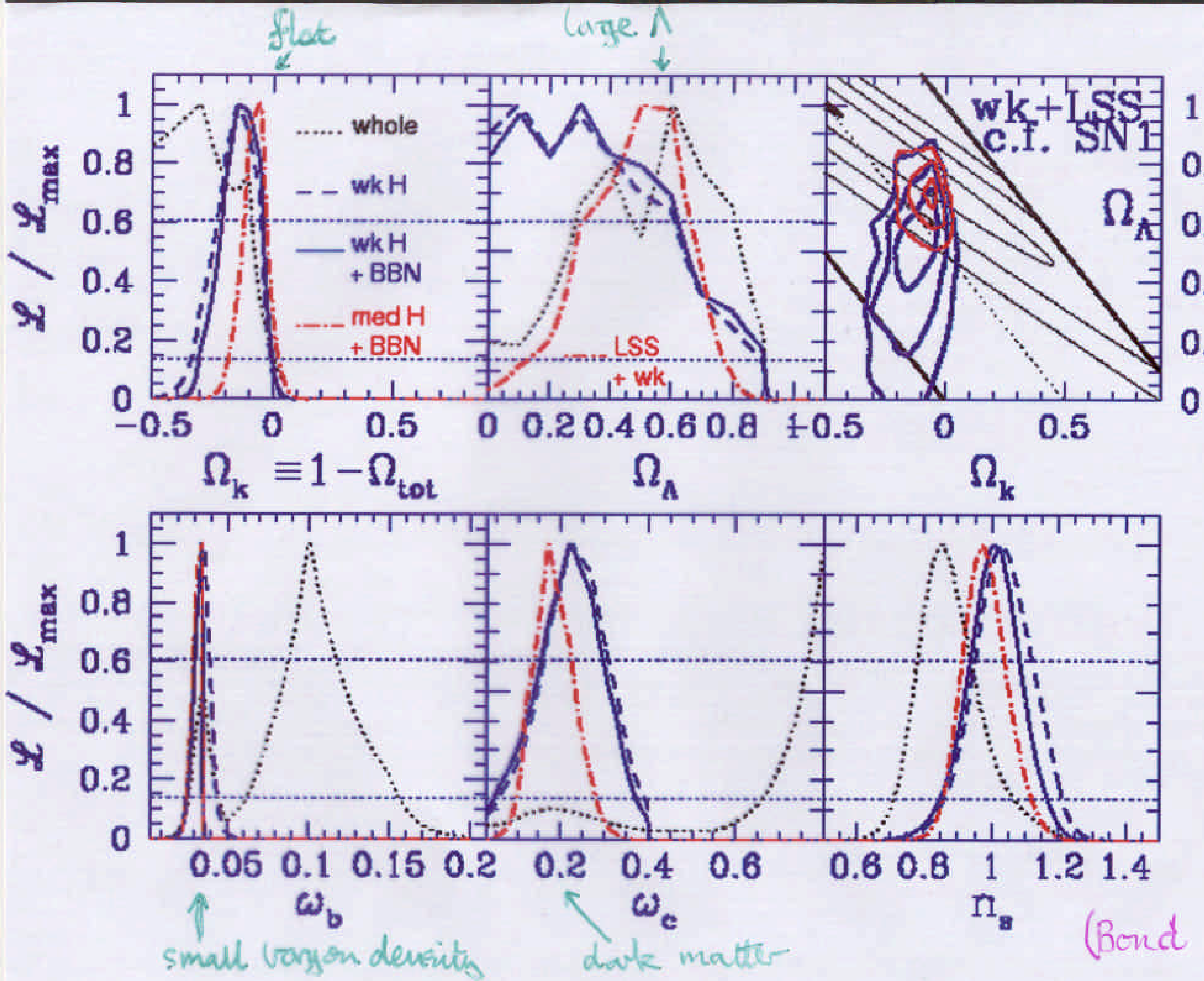
(Tegmark


Hata 1998 + Hu, Eisenstein & Tegmark 1998
ν_e–ν_μ limit
Cosmologically Excluded
ν_μ–ν_τ limit
LSND ν_μ- ν_e
Cosmologically Detectable
ν_μ–ν_s
ν_e–ν_s
BBN Limit
Cosmologically Important
Atmos ν_μ–ν_τ
Solar ν_e- $\nu_{\mu,\tau,s}$
Solar ν_e–$\nu_{\mu,\tau}$
Solar ν_e- $\nu_{\mu,\tau}$
Δm^2 (eV^2)
$\sin^2 2\theta$

closing in on the cosmological parameters with CMB et al.

(Tegmark




flat
large Λ
whole
wk H
wk H + BBN
med H + BBN
LSS + wk
wk+LSS
c.l. SN1
$\mathcal{L}/\mathcal{L}_{max}$
$\Omega_k \equiv 1 - \Omega_{tot}$
Ω_Λ
Ω_k
ω_b
ω_c
n_s
small baryon density
dark matter
(Bond

Can Neutrinos be Degenerate?

(J.E. + Lola)
(hep-ph/9904279)

$m_{1,2,3}$ ~ upper limit from { tritium β decay / astrophysics/cosmology }

$$m \sim 2\,\mathrm{eV} \gg \sqrt{\Delta m^2_{Atmo}} \gg \sqrt{\Delta m^2_{solar}}$$

strong constraint from absence of $\beta\beta_{0\nu}$ decay:

$$\langle m_\nu \rangle_e \simeq m \times \left| \underbrace{c_2^2 c_3^2 e^{i\phi} + s_2^2 c_3^2 e^{i\phi'}}_{\text{cancel!}} + \underset{\substack{\uparrow \\ \text{neglect: CHOOZ}}}{s_3^2} e^{2i\phi''} \right|$$

$$\lesssim 0.2\,\mathrm{eV}$$

$$c_2^2 - s_2^2 = \cos 2\theta_2 \lesssim 0.1 \quad \Rightarrow \quad \sin^2 2\theta_2 \gtrsim 0.99$$

maximal mixing necessary!

$\underbrace{\times\ \text{SMA},\ \text{also}\ \times\ \text{LMA}}$? $\leftarrow$ $\sin^2 2\theta_2 \lesssim 0.97$ ✓ vacuum oscillations

$\Rightarrow$ extreme degeneracy: $m \sim 10^{10} \times \sqrt{\Delta m^2_{solar}}$!

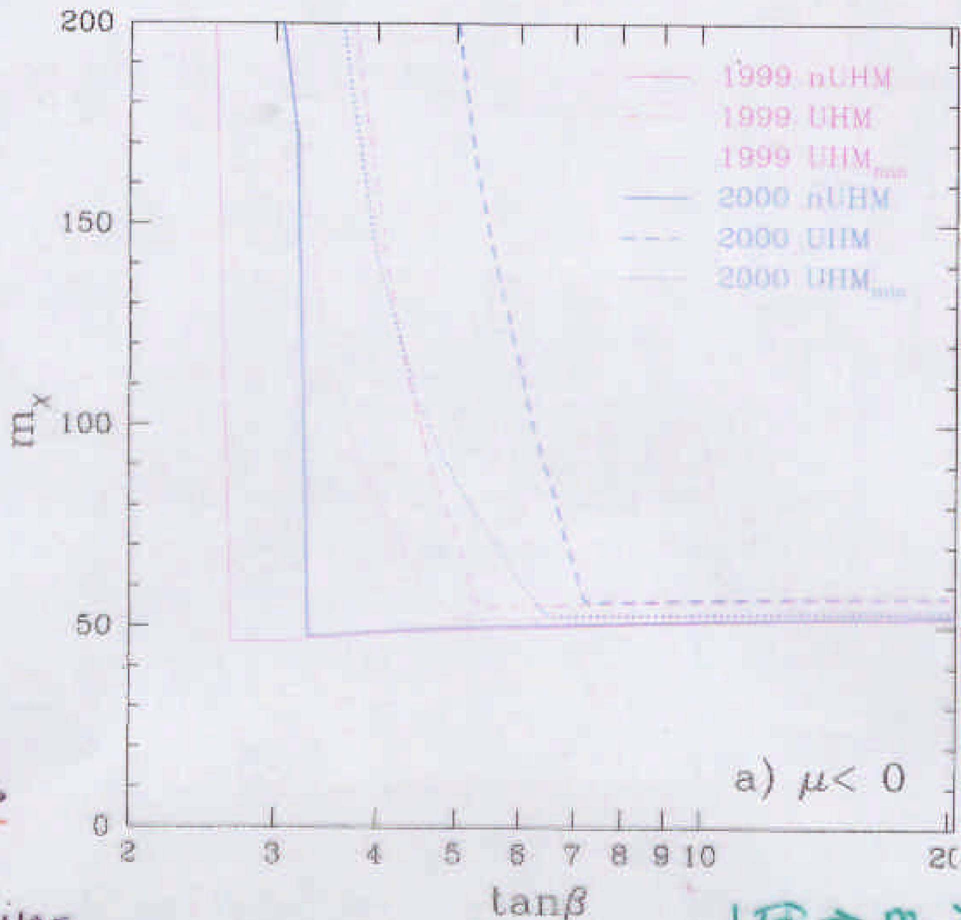
is this compatible with renormalization ?

$$\propto m_\mu^2,\ m_\tau^2,\ m_e^2$$

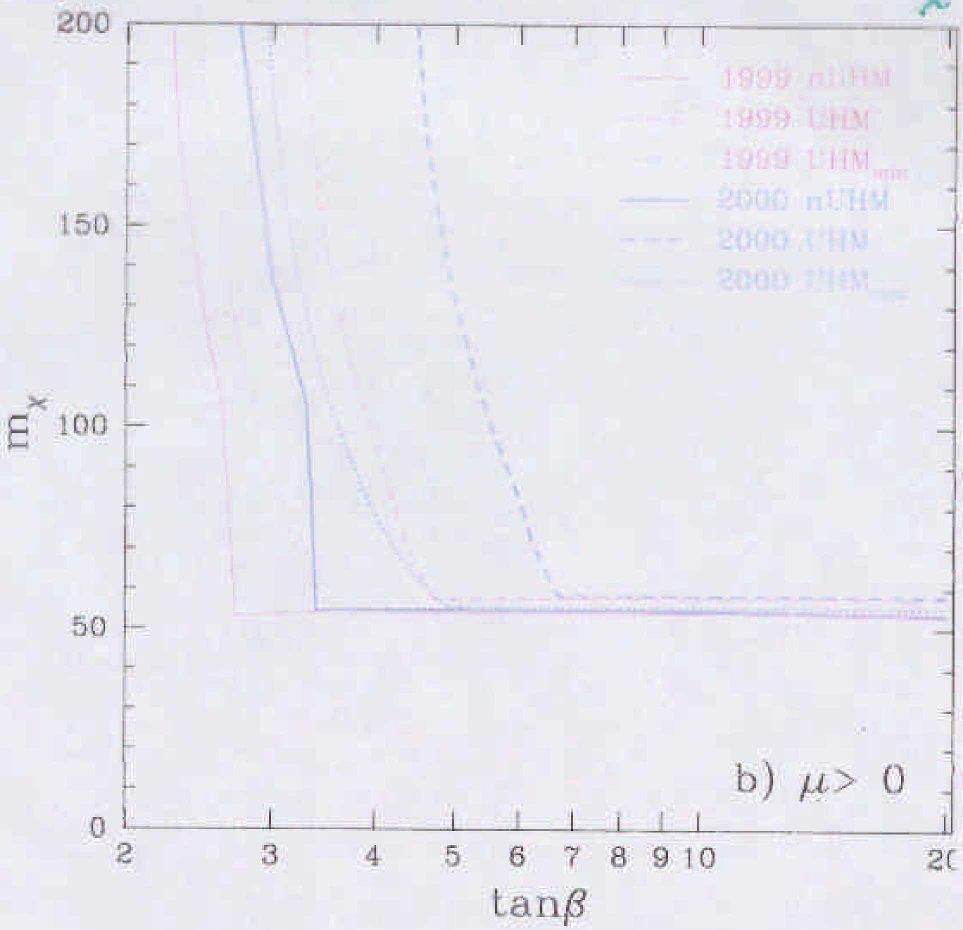
$\Rightarrow$ excessive breaking of degeneracy

lose maximal mixing

Lower Limits on Neutralino Mass



LEP $\Rightarrow m_\chi \gtrsim 50\,GeV$



(J.E.+Falk+Ganis+Olive)

Searches for Dark Matter Particles

focus on neutralinos

- Annihilation in galactic halo

$$\tilde{\chi}\tilde{\chi} \to l^+l^-, \bar{q}q \to \underbrace{\bar{p}, e^+, \gamma, (\nu)}_{\text{cosmic rays?}}$$

- Annihilation in Sun or Earth galactic centre?

  $\tilde{\chi}$ captured by elastic scattering, ΔE_{recoil}

  $$\tilde{\chi}\tilde{\chi} \to \underbrace{\text{"high energy"}\ \nu}_{\text{underground detectors: } \nu \text{ or } \mu} \quad \sim \text{GeV}$$

- Elastic Scattering in Laboratory

  $\tilde{\chi}N \to \tilde{\chi}N \Rightarrow$ detectable recoil energy

  $$E \sim \text{keV} \times \left(\frac{m_{\tilde{\chi}}}{4\,\text{GeV}}\right)$$

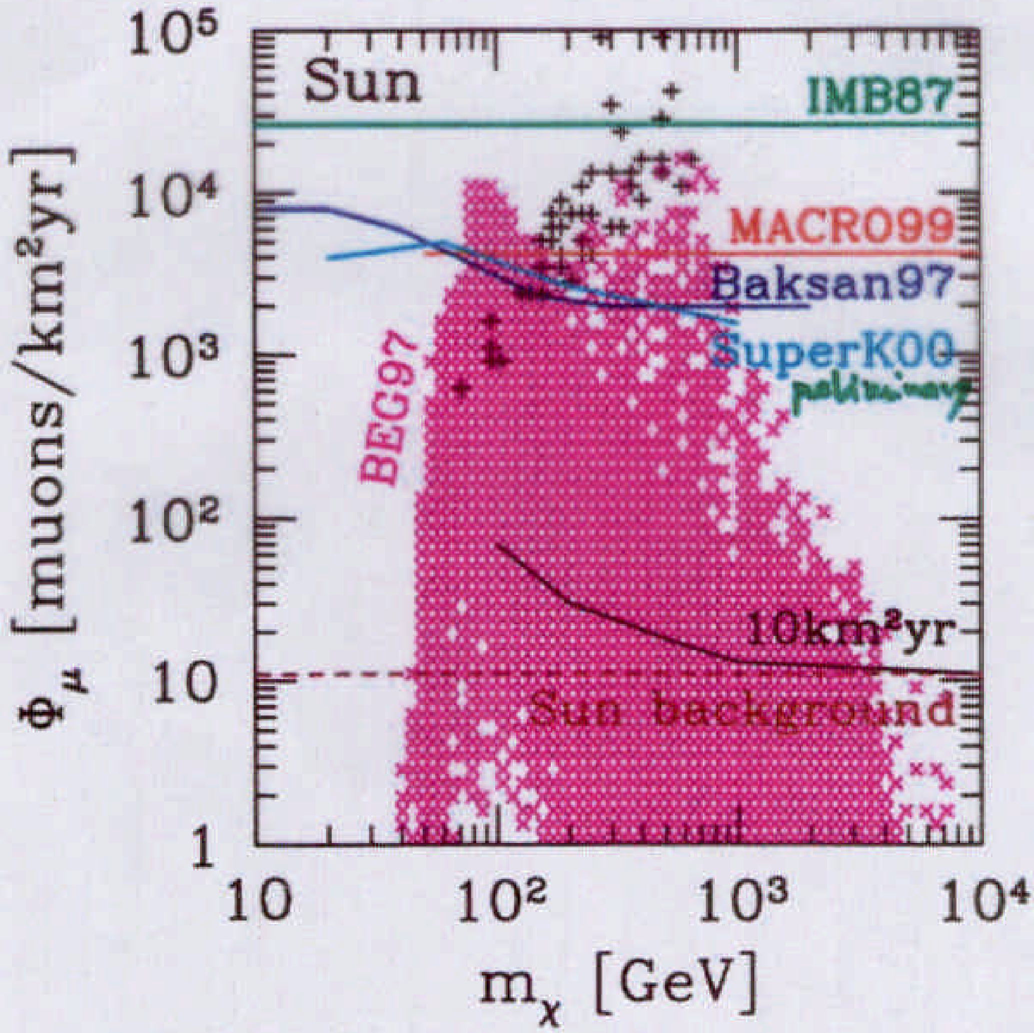
(- Inelastic Scattering

  $\tilde{\chi}N \to \tilde{\chi}(N^* \to N\gamma)$

  de-excitation ⊕ recoil energy: small rate)

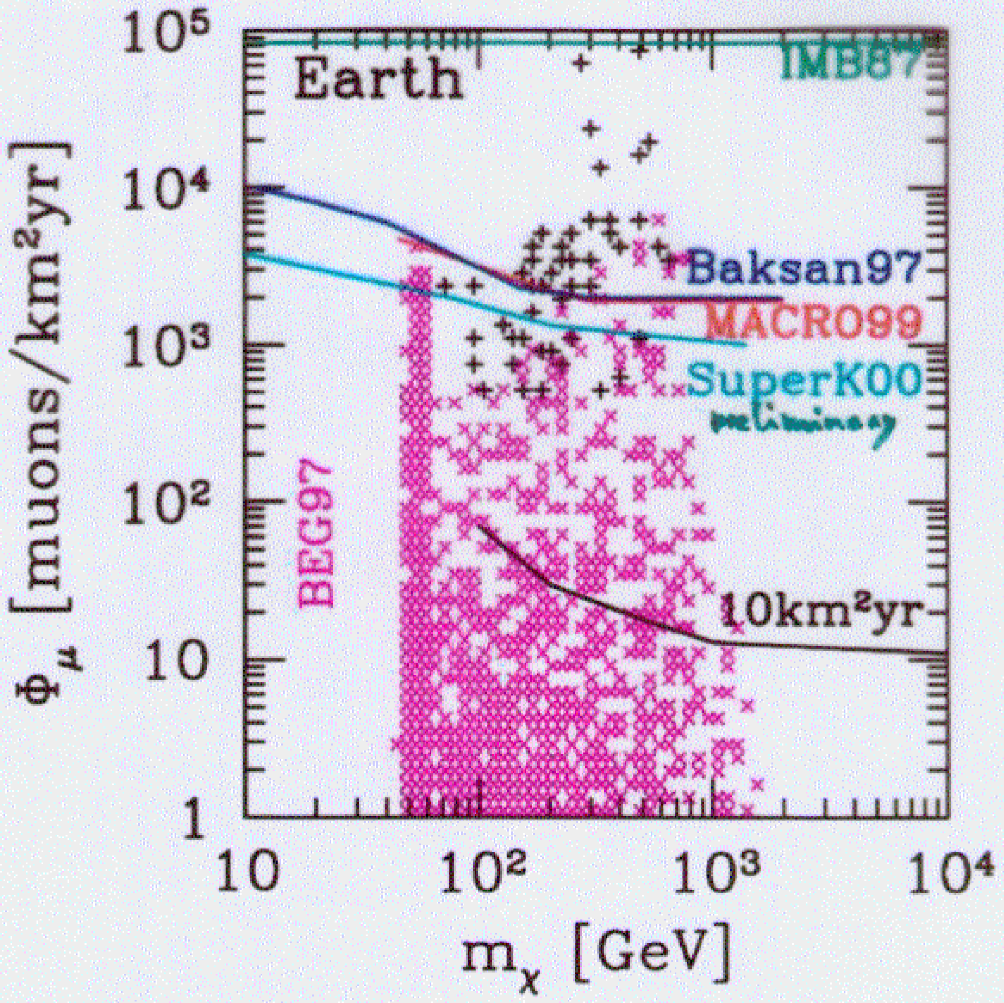
WIMP neutrinos from Sun

(Gondolo



WIMP neutrinos from Earth

(Gondolo



Caveat Neutrino Mixing

atmospheric, solar parameters may change flavour

(J.E.+ Flores + Masood

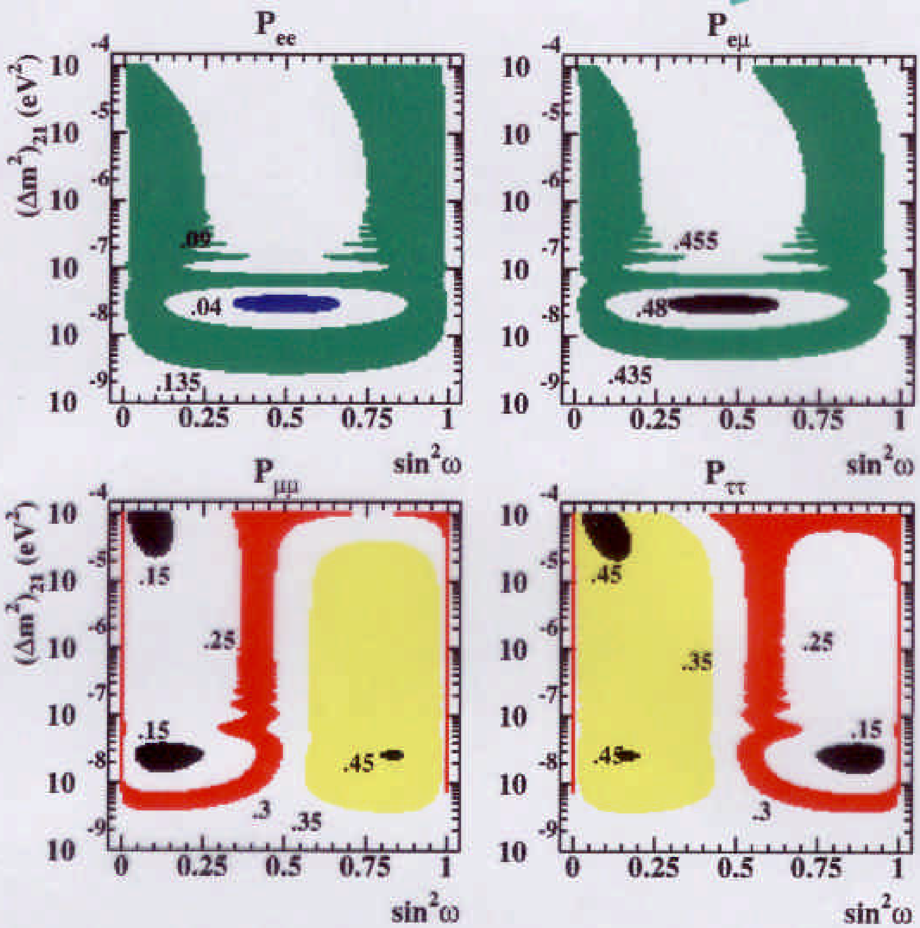


Figure 2: Constant $P_{\alpha\beta}$ contours in the $(\Delta m^2_{21} \times \sin^2\omega)$-plane, at ATM.

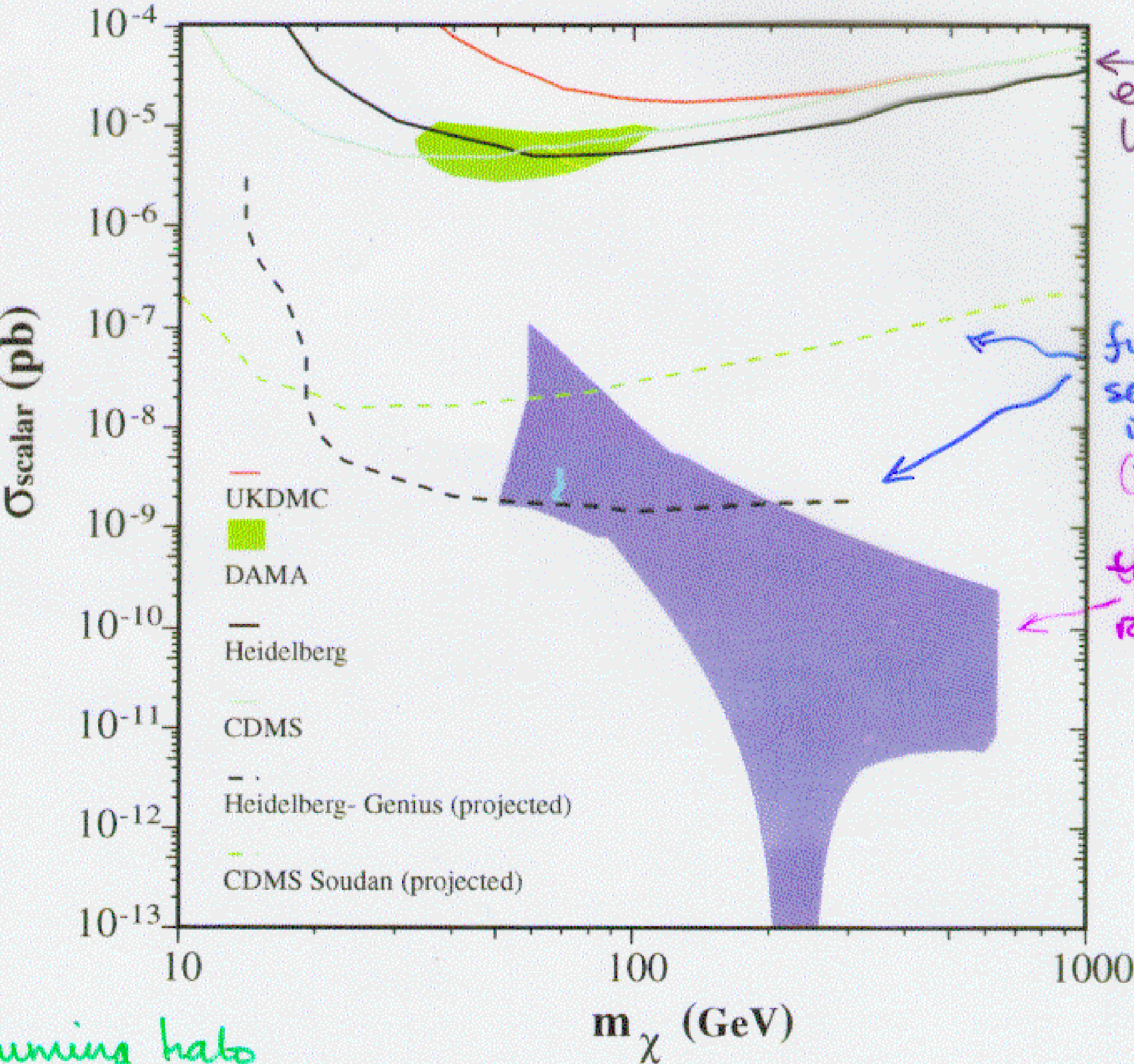
(de Gouvea

spin-independent

(Akerib
(Bernabei

Supersymmetric Dark Matter Cross Section

assuming m_0 universality



← exp'tal limits

future sensitivities (Zack

theory range

assuming halo dominated by supersymmetric dark matter

Griest)

Milsztajn)

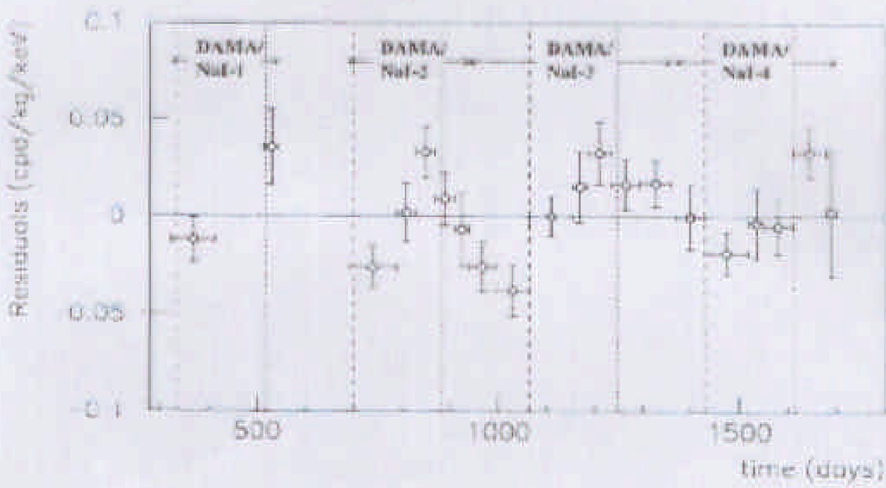
(J.E. + Ferstl + Olive
hep-ph/0001005 → PLB

Model independent result from DAMA

- 4 yearly cycles
- Exposure of 57986 kgday
- Residuals of rate vs time
- Low energy region: 2-6 keV interval

(Bernabei

Zero of the time scale:
January 1st of the first year of data taking



what is being modulated? e? γ? n? nuclear? recoil?

$$A \cos[\omega(t-t_0)]$$

$$\chi^2_0(A=0)/\text{dof} = 48/20 \qquad (P = 4 \times 10^{-4})$$

1) t_0 = 152.5 days (fixed)
 A = (0.022±0.005) cpd/kg/keV
 $T = 2\pi/\omega$ = (1.00±0.01) years
 $\chi^2/\text{dof} = 23/18$

2) T = 1 year (fixed)
 A = (0.022±0.005) cpd/kg/keV
 t_0 = (144±13) days
 $\chi^2/\text{dof} = 23/18$

SIMILAR RESULTS, BUT WITH LARGER ERRORS IN CASE ALL PARAMETERS ARE KEPT FREE

7- High-Energy Astrophysical Neutrinos

- First experiments taking data (AMANDA: Barwick (Baikal: Domogatsky
- Beginning to challenge some models

  AGNs, GRBs, ... (Gandhi
- More detectors underway (NESTOR: Resvanis (ANTARES: Thompson
- Concepts for large detectors:

  Mediterranean, ICECUBE, acoustic, radio, EUSO (Spiering, Weiler

Probes of fundamental physics?

Constrain modification of special relativity

$$c(E) = c_0 (1 - E/M) \; : \; M \gtrsim 10^{15}\,\mathrm{GeV}\;^{*}$$

HE γ's from AGNs, GRBs (Amelino-Camelia, J.E. et al.

Mukherjee)

Could wash out ν pulses! (Waxman (Letessier-Selvon

Absence of GZK cutoff? γ cutoff? (Protheroe + Meyer

nearby sources? $\nu\bar{\nu} \to Z$, heavy particle decays

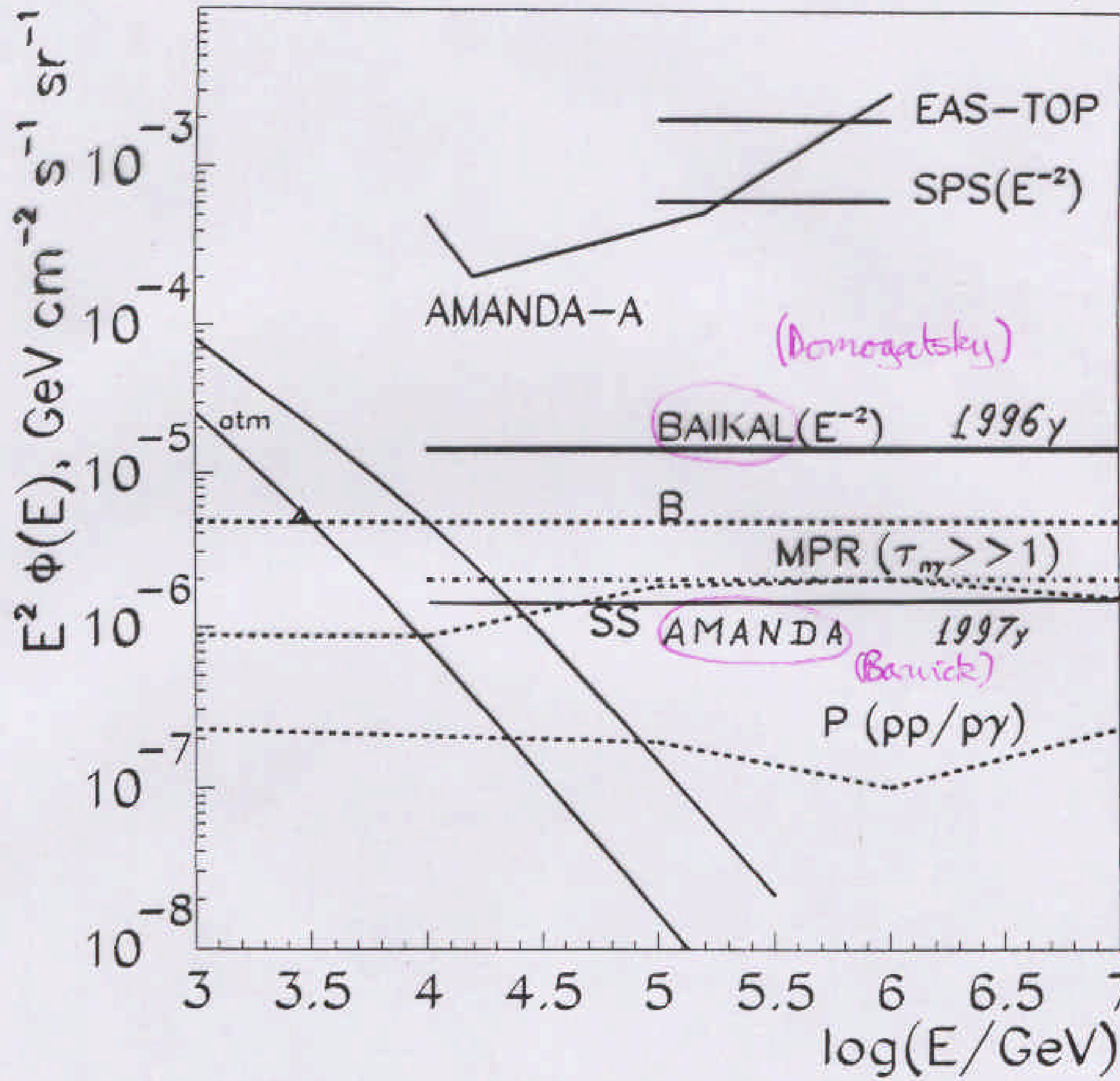
* modify collision / decay kinematics? (Gonzalez-Mestres, Coleman + Glashow

VERY HIGH ENERGY NEUTRINOS

experiments begin to probe predictions (Gandhi)

[redacted]

NT-96



$$\tilde{\nu}_e + e^- \Rightarrow W^- \Rightarrow \text{anything} \qquad E_0 = 6.3\cdot 10^6\,\text{GeV}$$

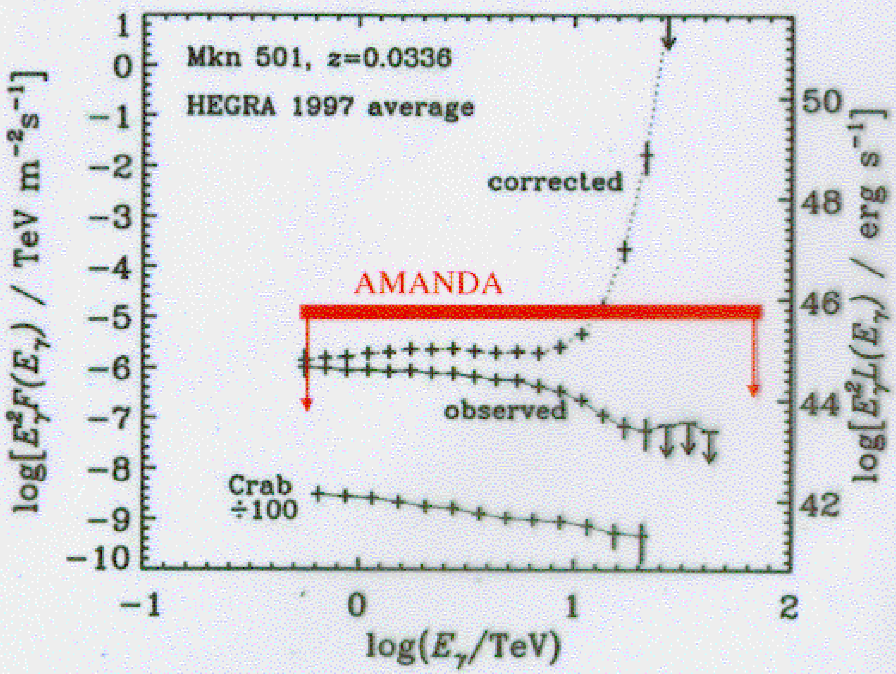
$$\begin{cases} \nu_e(\tilde{\nu}_e) + N \overset{CC}{\Rightarrow} \ell^-(\ell^+) + \text{hadrons} \\ \nu_\ell(\tilde{\nu}_\ell) + N \overset{NC}{\Rightarrow} \nu_\ell(\tilde{\nu}_\ell) + \text{hadrons} \end{cases}$$

AMANDA

Mk 501 Flux Limit

- Recent diffuse IR measurements imply strong attenuation of TeV photons
- AMANDA can rule out similar neutrino spectrum.

Figure adapted from Protheroe and Meyer, astro-ph/0005349



Basic Concept for ν Factory (Keil

p beam power: $P \sim 4$ MW (1 to 20)

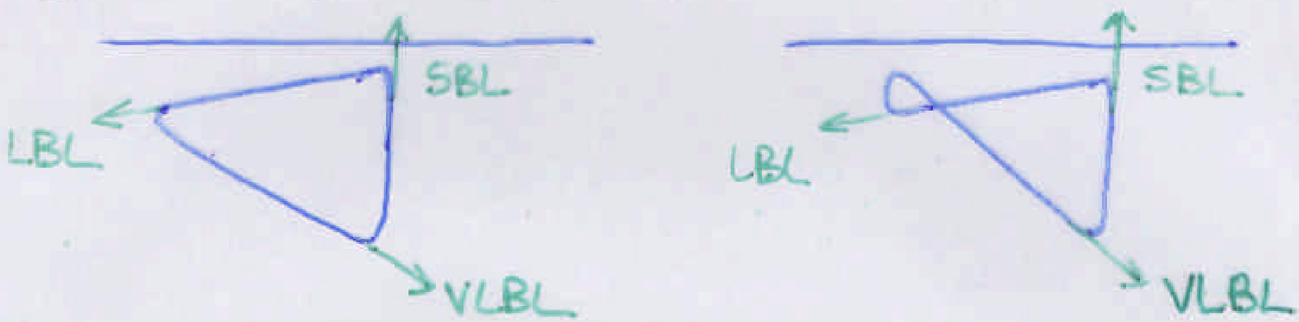
↳ linac or rapid-cycling synchrotron?

1.5×10^{15} p/s @ 16 GeV (few to 30)

capture $0.2\,\mu/p$ cool $0.1\,\mu/p$

storage ring: $3 \times 10^{20}\ \bar{\nu}_\mu, \nu_e/y$ in given direction

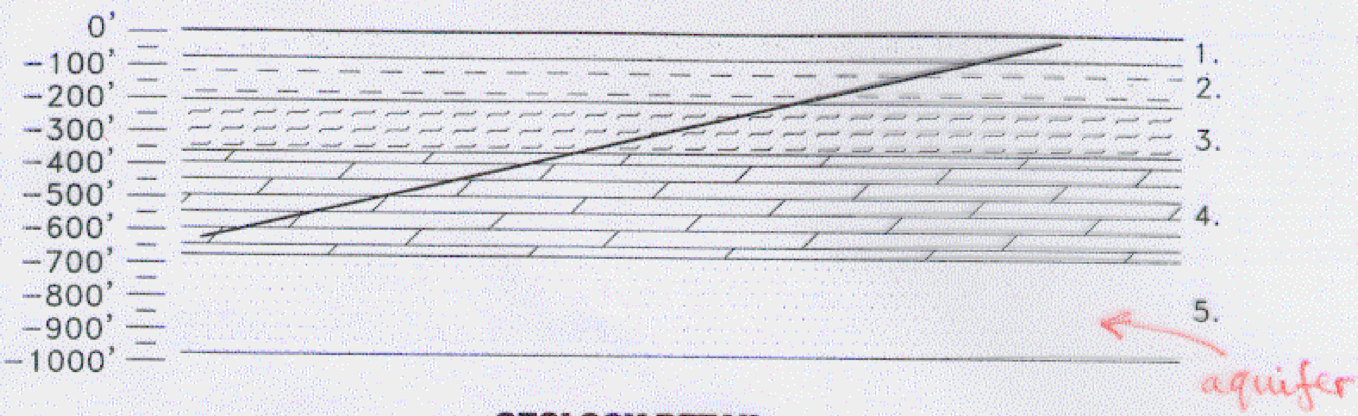
generic geometry: $E_\mu \sim 10$ to 50 GeV



Issues:

- target: LHg vs moving solid?
- capture: 20T solenoid
- monochromator: pulsed warm RF, 5 to 8 MV/m
- cooling: 1/30 vs 10^{-6} for collider
- acceleration: LEP RF?
- radiation: 10m rock/concrete around target

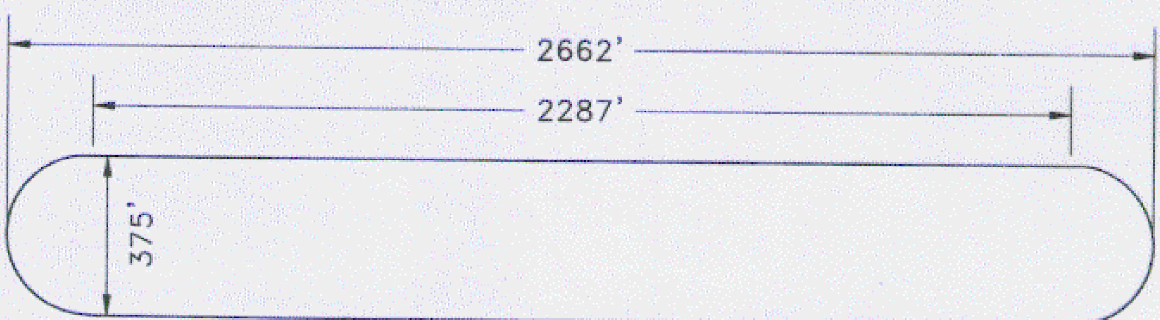
ν factory design @ FNAL



GEOLOGY DETAIL

1"=100'-0"

1. GLACIAL TILL – AQUIFER
2. SILURIAN GROUP – AQUIFER (PRIMARILY DOLOMITE)
3. MAQUOKETA GROUP – AQUIFER (PRIMARILY SHALE)
4. GALENA / PLATTEVILLE GROUP – AQUATARD (PRIMARILY DOLOMITE)
5. ANCEL GROUP – AQUIFER (PRIMARILY SANDSTONE)



39.8% = (ONE STRAIGHT SECTION/PERIMETER)*100

CJ 2.0 LATTICE PLAN

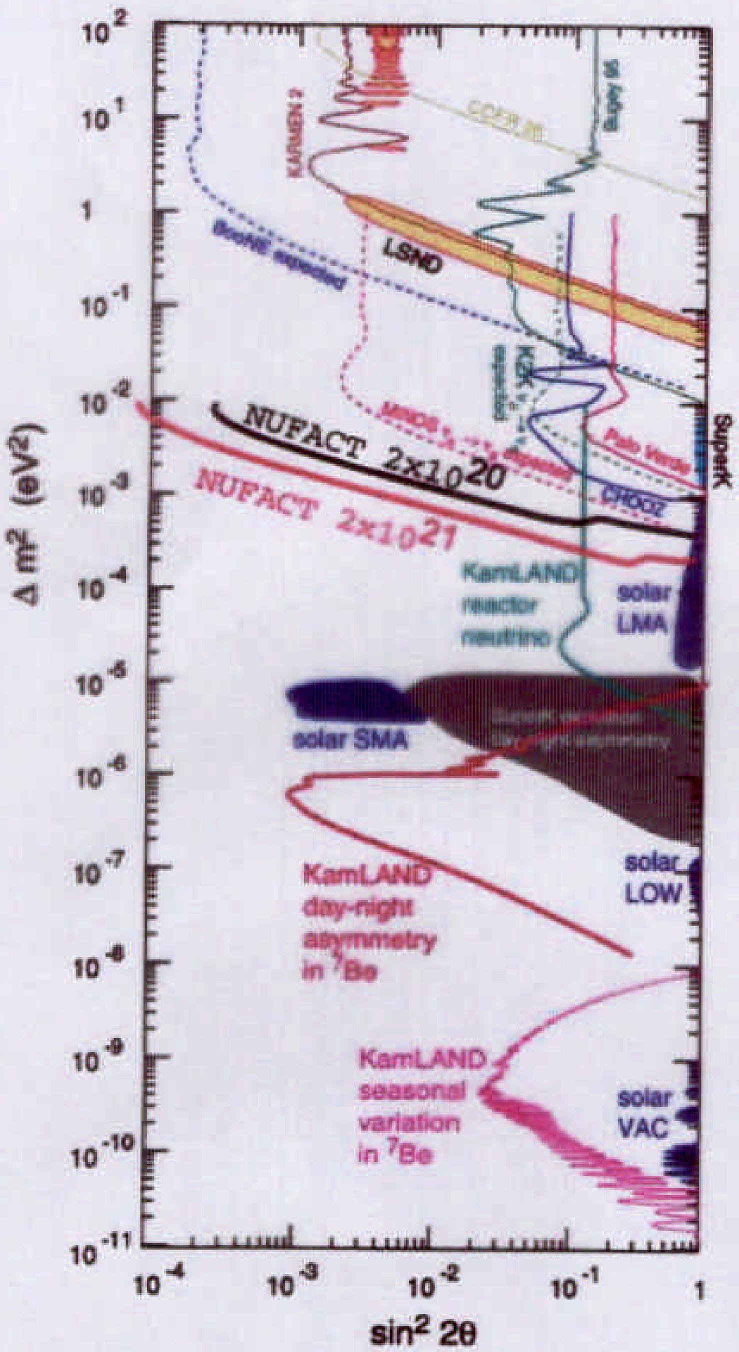
N.T.S.

ORIENTATION:

NAME	AZIMUTH (DEG–MIN–SEC)	VERT. ANGLE (DEG–MIN–SEC)	DISTANCE (KM)
PALO ALTO CA.	271–20'–42.27"	–13–09'–26.99"	2910

(Holtkamp, Finley et al.)

MuSR
CTE 11-NOV-99



(Schellman

Limits on $\sin^2\theta_{13}$ for a 10kt detector 7400 km away.

Bueno *et al.*

CP Violation, T Violation, Matter Effects

(De Rujula

$$A_{CP} = \frac{(\nu_\mu \to \nu_e) - (\bar{\nu}_\mu \to \bar{\nu}_e)}{+}, \quad A_T = \frac{(\nu_\mu \to \nu_e) - (\nu_e \to \nu_\mu)}{+}$$

may be large,
but beware of MSW!

needs $e^\pm$ discrimination:
difficult?

$$A_{CP} \simeq \frac{4 \sin 2\theta_{12} \sin\delta}{\sin\theta_{13}} \cdot \sin\left(\frac{2\Delta m^2_{12} L}{4E}\right)$$

need large Δm^2_{12}, θ_{12}

measurable for large-mixing-angle solution to solar neutrino deficit

✓Super-K

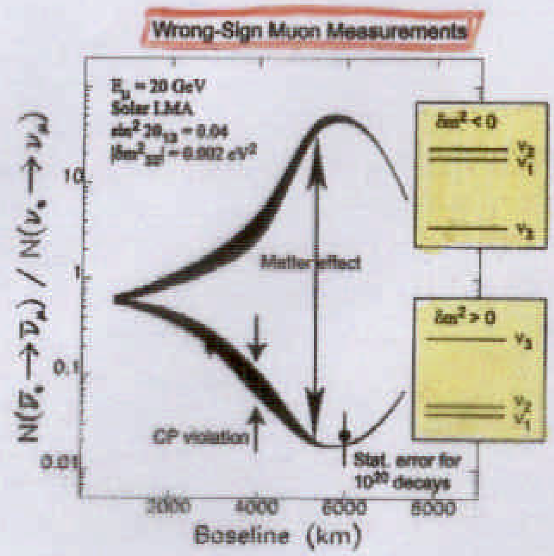
baseline ~ 3000km

5σ for 50kt × 5y × 20 MW

$$A_{MSW} \simeq 0.7 \times 10^{-6} \times \frac{L^2 (\mathrm{km}^2)}{E\ (\mathrm{GeV})}$$

for $\Delta m^2_{23} \sim 3 \times 10^{-3}\ \mathrm{eV}^2$

dominant for baseline $\gtrsim$ 4000 km



$\dfrac{\mu^+ \text{ in } \mu^- \text{ BEAM}}{\mu^- \text{ in } \mu^+ \text{ BEAM}}$

Figure I: Predicted ratios of $\bar\nu_e \to \bar\nu_\mu$ to $\nu_e \to \nu_\mu$ rates at a 20 GeV neutrino factory. The upper (lower) band is for $\delta m^2_{32} < 0$ ($\delta m^2_{32} > 0$). The range of possible CP violation determines the widths of the bands. The statistical error shown corresponds to 10^{20} muon decays of each sign and a 50 kt detector. Results are from Ref. 51.

↳ ~~PRESUMABLY~~ BARGER/GEER/RAJA/WHISNANT

(De Rujula

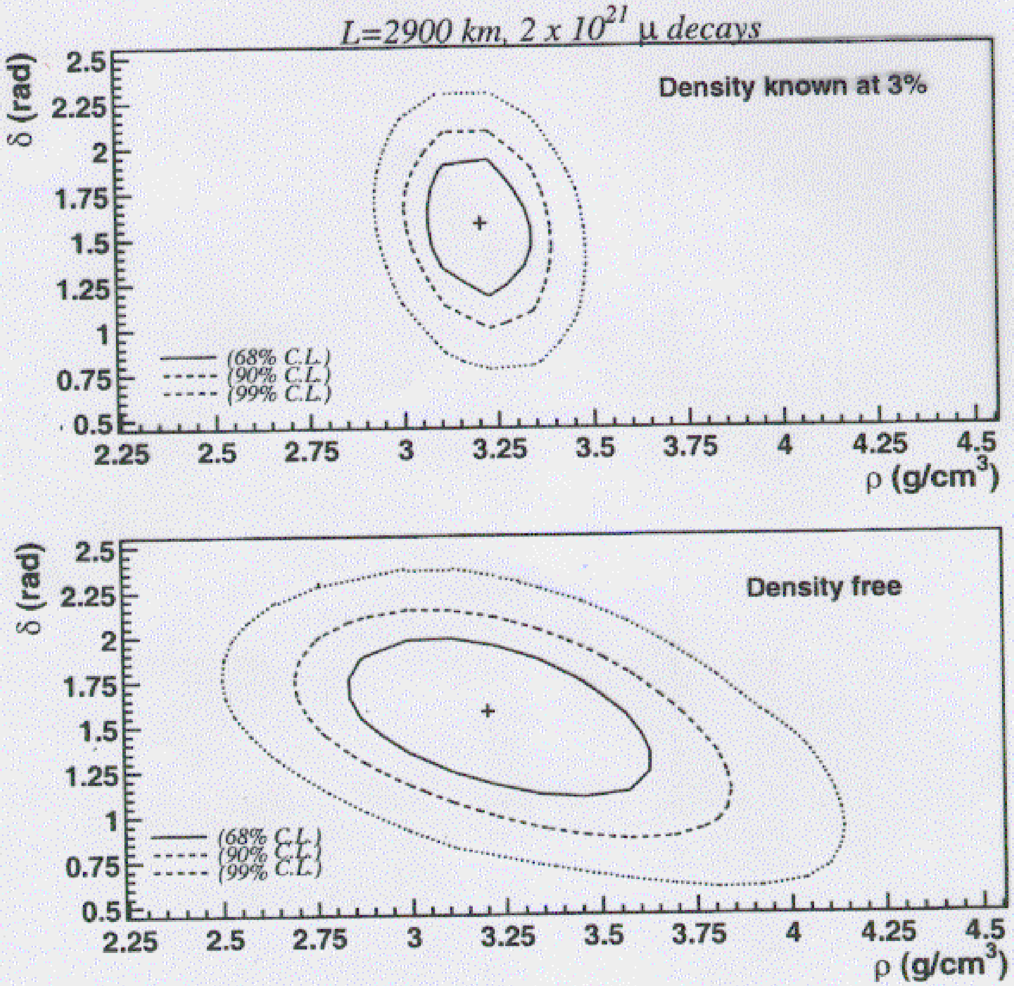
(Schellman

Sensitivity to CP-Violating Phase

only if large-mixing-∠
MSW solution to solar ν !

@ 2900 km

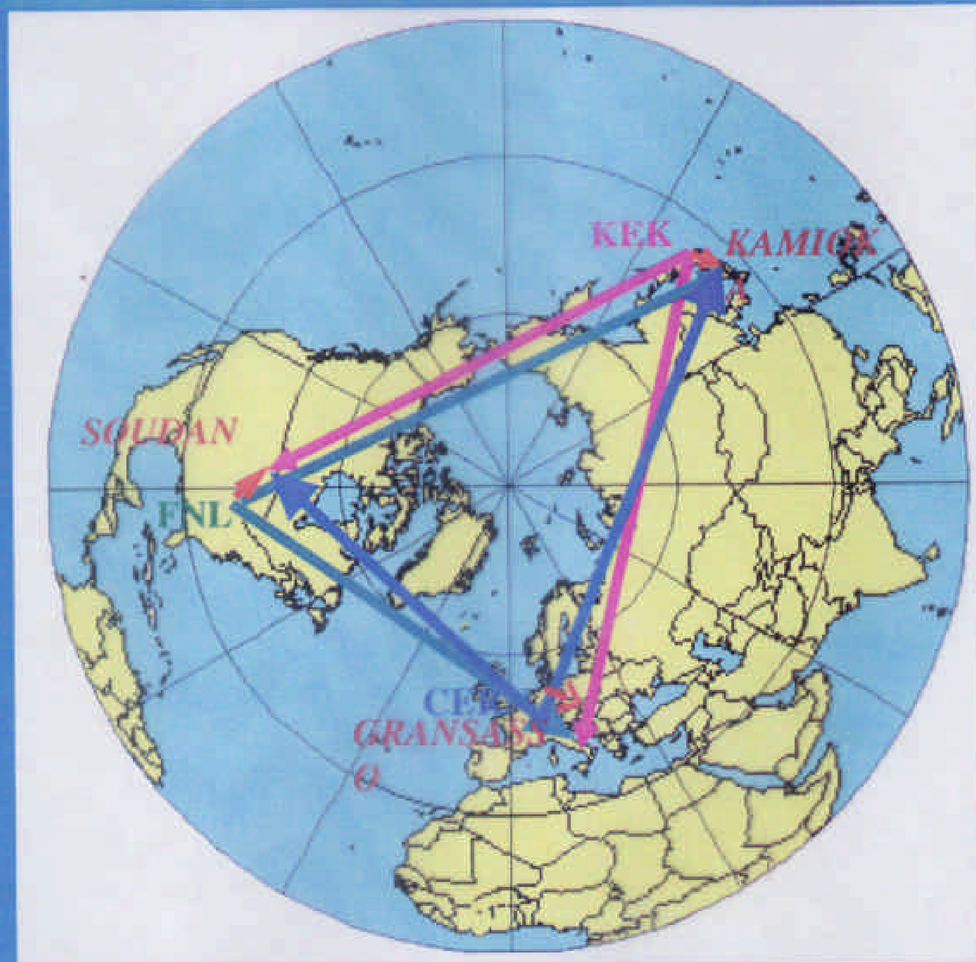
(De Rujula



How well do we know the density of the Earth?

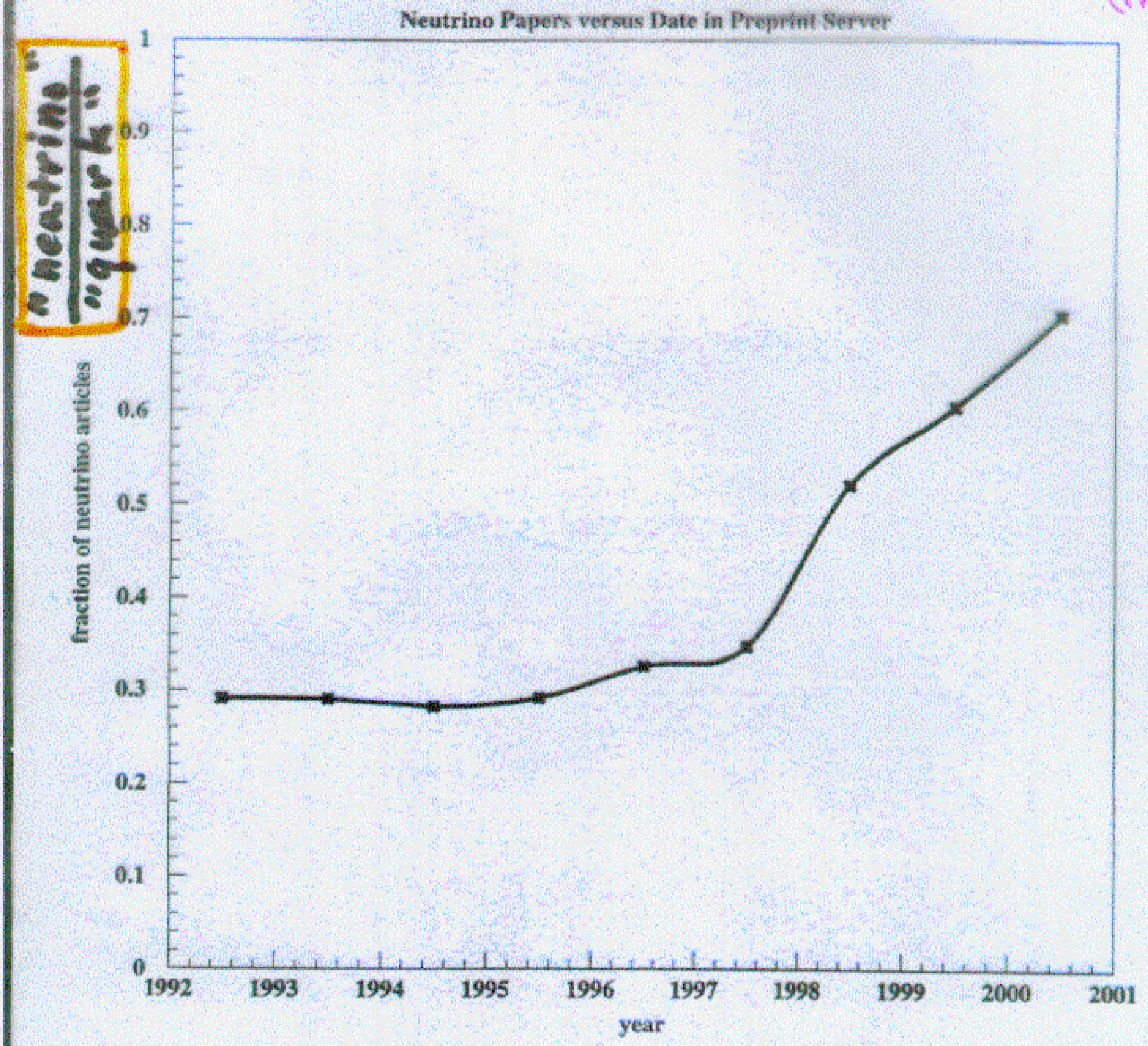
(Bueno + Campanelli
+ Rubbia'
hep-ph/0005007

Un Web mondial pour les neutrinos ?



(Maiani

(Weiler



from John Learned

ν factory is very attractive:

good physics (getting better...)

world machine?

intellectually/technically challenging

but many questions remain:

LMA for solar neutrinos?

target?

$\boxed{\text{cooling}}$?

engineering of ring? (steep slope for 7000km)

it will not be cheap!

wise to reach out to other communities:

"standard" ν, μ scattering (McFarland

stopped-muon physics

K physics? (if high-E proton driver)

beyond particle physics

direct beam(s) to large underground detector