united nations educational, scientific and cultural organization

international atomic energy agency

the **abdus salam** international centre for theoretical physics

SMR.1317 - 19

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

NEUTRINO PHYSICS

Lecture III

E. LISI
Istituto Nazionale di Fisica Nucleare
Department of Physics
University of Bari
Bari, ITALY

Please note: These are preliminary notes intended for internal distribution only.

Lecture III

2ν phenomenology of:

- **Atmospheric ν**

  evidence for $P(\nu_\mu \to \nu_\mu) < 1$

  $\to$ ν_μ flavor disappearance

- **Solar ν**

  evidence for $P(\nu_e \to \nu_e) < 1$

  $\to$ ν_e flavor disappearance

- **CHOOZ reactor ν**

  <u>NO</u> evidence for $P(\nu_e \to \nu_e) \neq 1$

  $\to$ important constraints

- **LSND accel. ν**

  Controversial evidence for $P(\nu_\mu \to \nu_e) > 0$

  (appearance of flavor)

PHENOMENOLOGY:

COMPARISON OF MODELS WITH DATA IS NOT STRAIGHTFORWARD

MODELS $\equiv P(\nu_\alpha \to \nu_\beta)$

OBSERVABLES $\equiv$ lepton rates $R_{\alpha,\beta}$

$$R_\beta \sim \sum_\alpha \int \phi_\alpha \otimes P_{\alpha\beta} \otimes \sigma_\beta \otimes \epsilon_\beta \pm \sigma_\beta$$

- R_β ↑ lepton rate ↑ what we see
- ϕ_α ↑ ν flux
- $P_{\alpha\beta}$ ↑ transit. probabil. ↑ what we test
- σ_β ↑ cross sect.
- ϵ_β ↑ detector effic. & resol.
- $\pm \sigma_\beta$ ↑ uncertainties (theo + expt.)

Constraints on $P_{\alpha\beta}$ are obtained by comparison of R_β^{exp} with R_β^{theo}, tipically through a χ^2 statistics

$$\chi^2 = \sum_{\text{observables}} \frac{(\text{THEORY} - \text{EXPT.})^2}{\text{ERROR}^2} \quad \text{(simbolycally)}$$

TWO USES OF χ^2: (Particle Data Group)

GOODNESS-OF-FIT

Compare χ^2 (for a given model) with

N_{dof} = N(DATA) − N(MODEL FREE PARAMET.)

If $\chi^2/N_{dof} \sim 1$ → MODEL OK

PARAMETER ESTIMATE

If previous model passes goodness-of-fit test, then take best-fit model parameters (minimizing χ^2) as "true" values, and attach them errors by appropriate iso-$\Delta\chi^2$ levels ($\Delta\chi^2 = \chi^2 - \chi^2_{min}$) for

N_{dof} = N(MODEL FREE PARAMETERS)

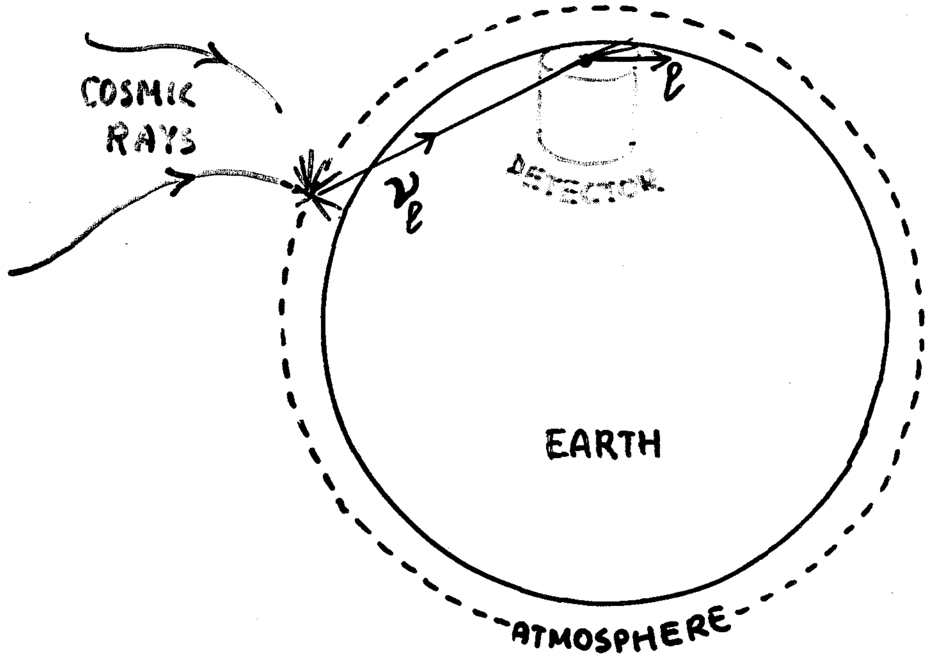
E.g. $\Delta\chi^2 = 4.61$ gives 90% C.L. errors for $N_{dof} = 2$

VAST MAJORITY OF χ^2-derived FIGURES IN PHENOMENOLOGICAL LITERATURE REFERS TO PARAMETER ESTIMATE (goodness-of-fit test proven or assumed to be satisfied)

ATMOSPHERIC ν

Atmospheric $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ are generated as decay products* in showers induced by cosmic rays

They can be detected through CC interactions in underground detectors (SuperKamiokande, MACRO, Soudan2, ...)



---

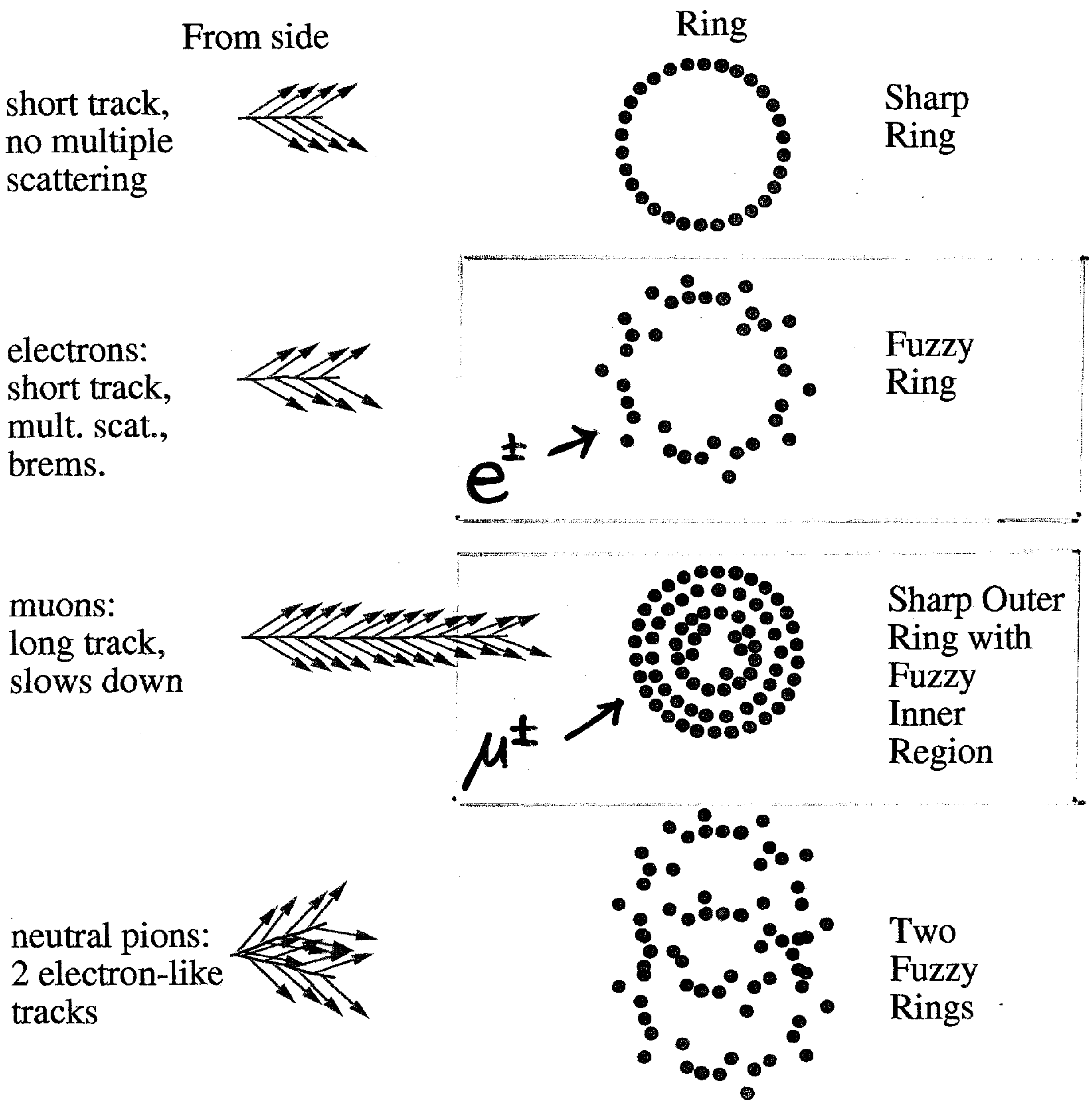
* mainly from pion decay

$\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm + 2\overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_e$

$\overset{(-)}{\nu}_e$ produce $e^{\pm}$; $\overset{(-)}{\nu}_{\mu}$ produce $\mu^{\pm}$

HOW DO THEY LOOK LIKE IN SK ?

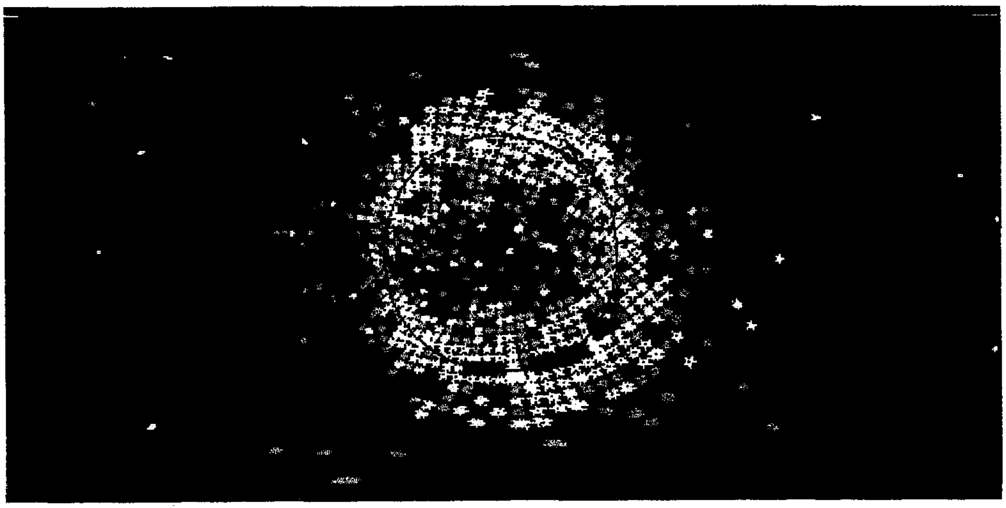
Particle ID in a Cerenkov Detector:



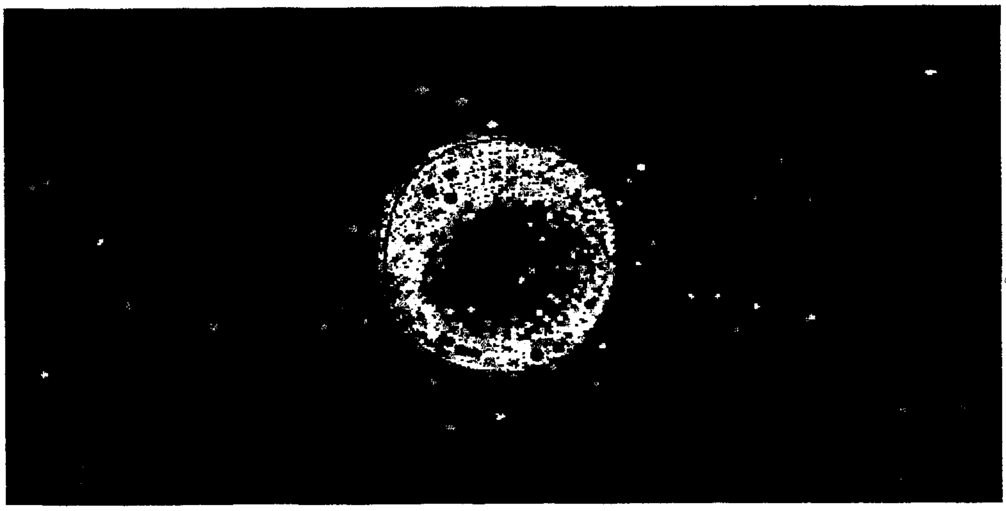
Real SK events

Particle Identification

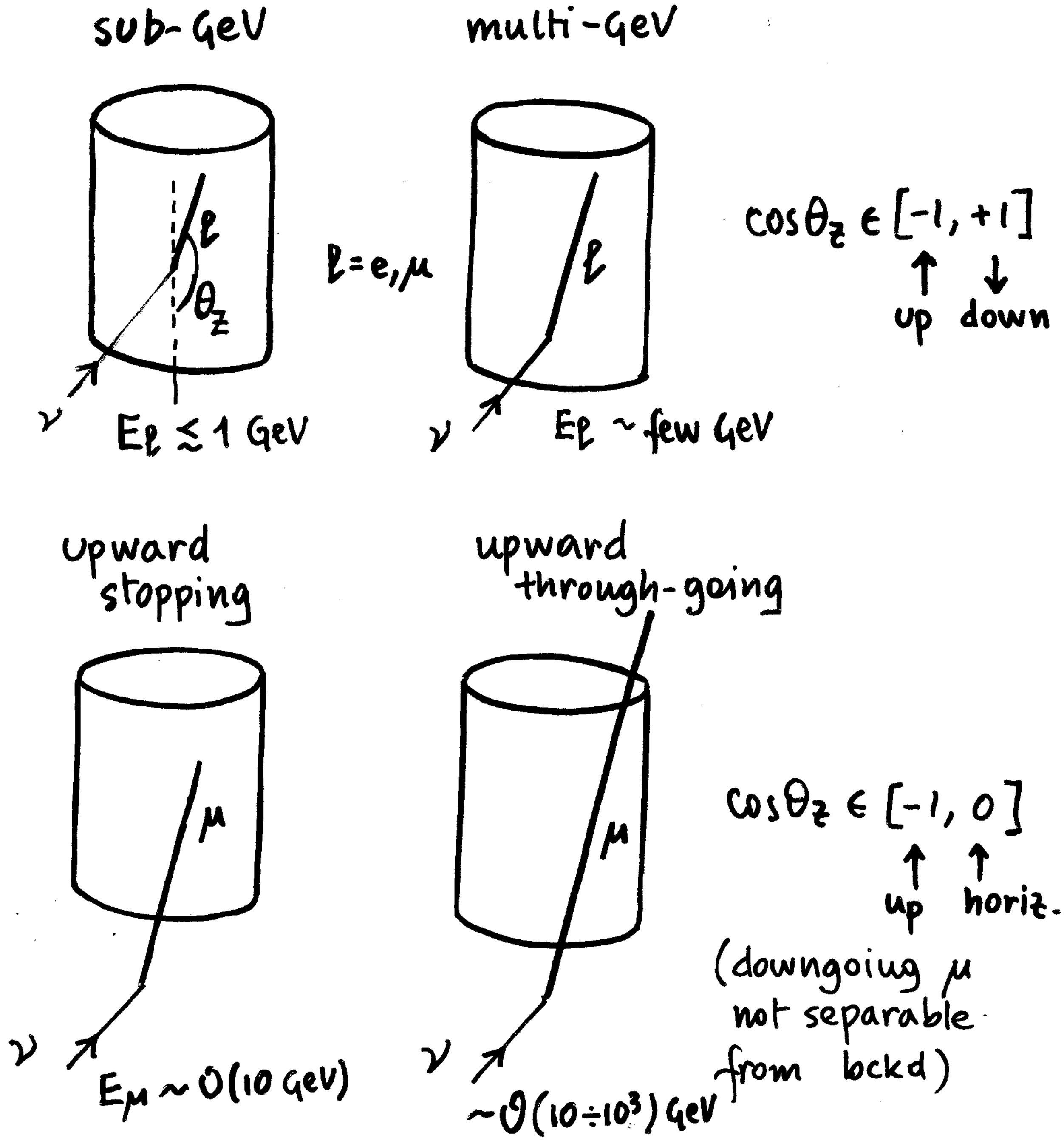
- Must distinguish electrons: e



- From muons: μ



SuperK. JARGON



- Range of E_ν probed: $\sim 10^{-1} \div 10^{3}$ GeV
- Range of L probed: $\sim 10 \div 10^{4}$ km

→ "wide-band" experiment

∼ MODEL-INDEPENDENT RESULTS:

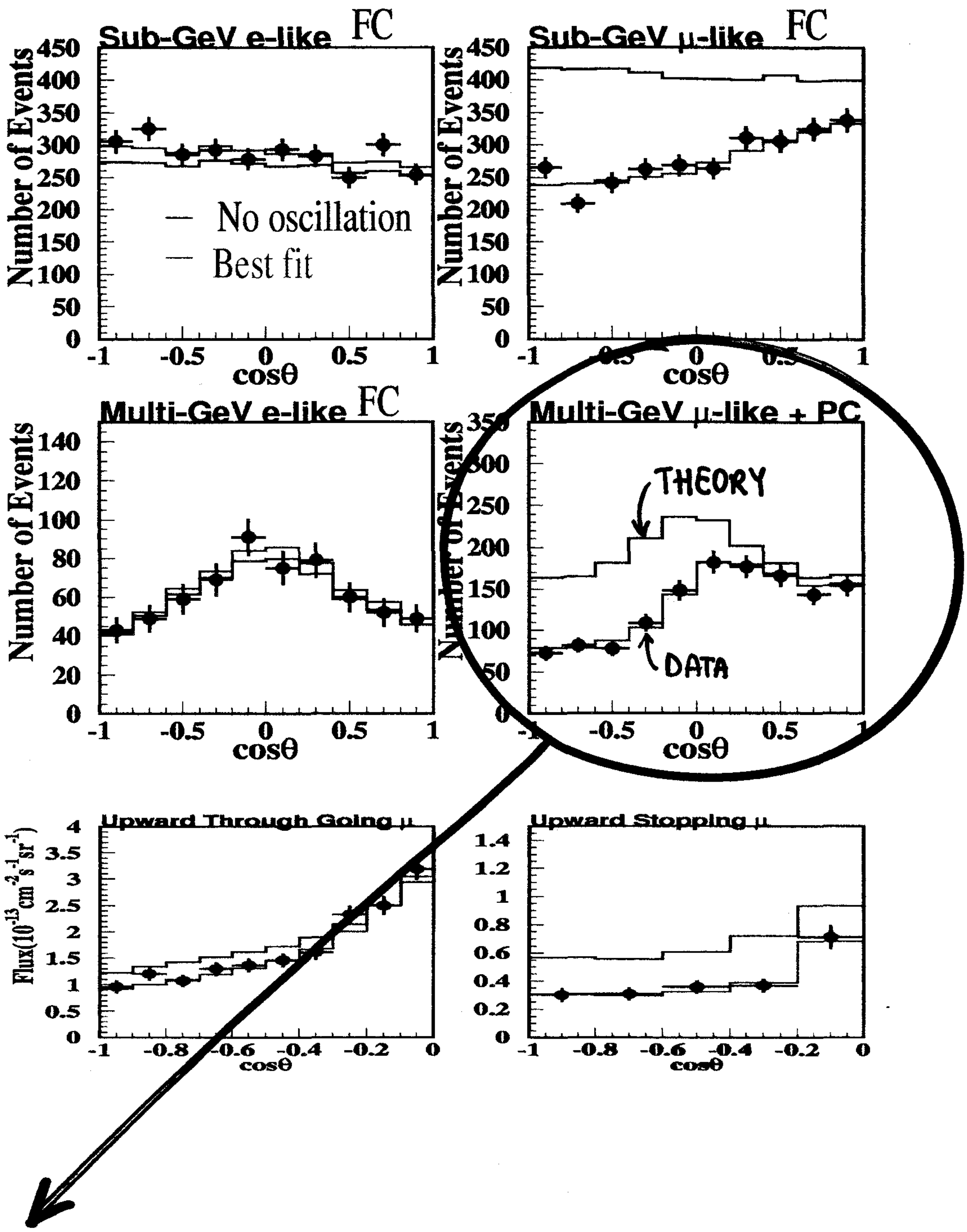
(not affected by large normaliz. errors)

for no oscillation

PREDICTION	REASON	DATA
$\frac{\Phi(\nu_\mu)}{\Phi(\nu_e)} \sim 2$	$\pi^\pm$ decay	$\frac{\Phi(\nu_\mu)}{\Phi(\nu_e)} \sim 1.2$
$\Phi^\uparrow(\nu_e) \simeq \Phi^\downarrow(\nu_e)$	Spherical source	$\Phi^\uparrow(\nu_e) \simeq \Phi^\downarrow(\nu_e)$
$\Phi^\uparrow(\nu_\mu) \simeq \Phi^\downarrow(\nu_\mu)$	Spherical source	$\Phi^\uparrow(\nu_\mu) < \Phi^\downarrow(\nu_\mu)$

↑ Super-Kam. (SK) breakthrough

LATEST SK DATA



UP/DOWN ASYMMETRIC DEFICIT OF OBSERVED MUONS

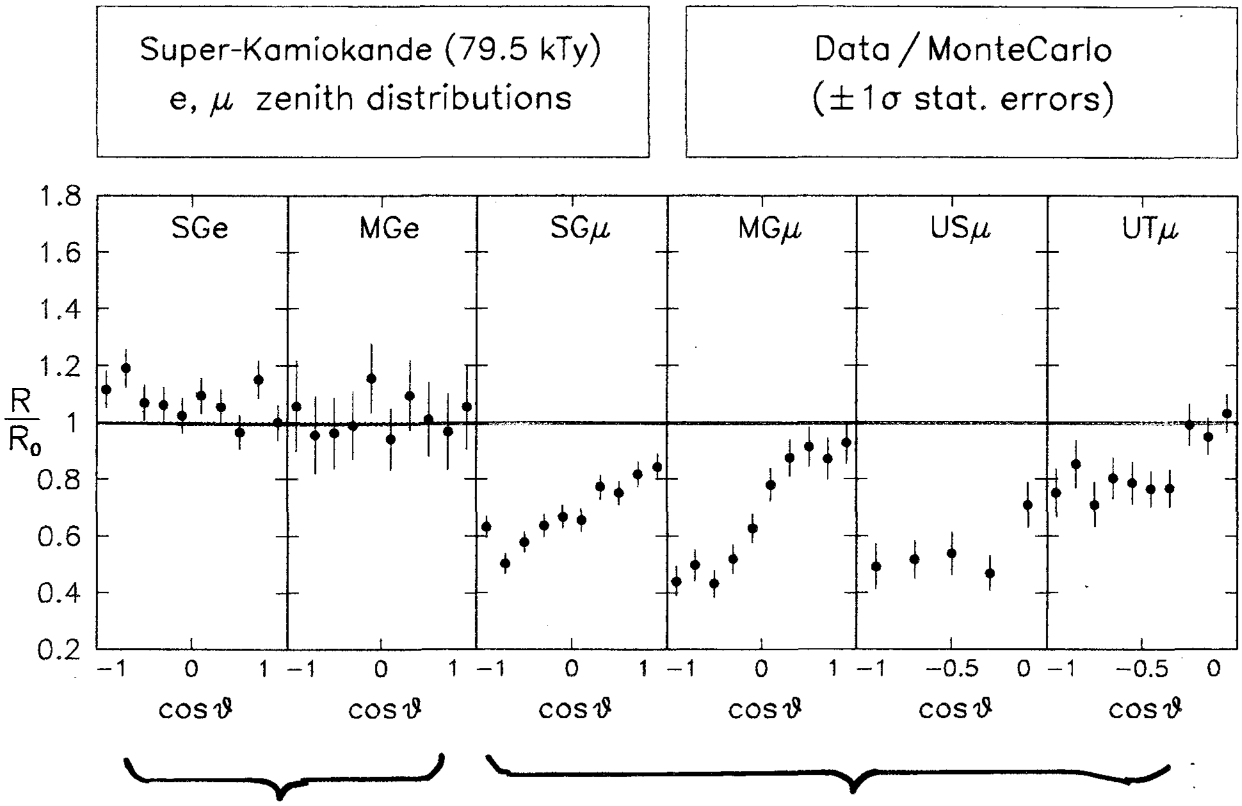
3

Another represent. of the same data:

SG = SubGeV
MG = Multi GeV
US = Upward stopping
UT = " through-going

——— Predictions (no osc.)

ɸ SK data (2001)



electrons muons

$\cos\theta = -1$: upgoing leptons

$\cos\theta = 0$: horizontal "

$\cos\theta = +1$: downgoing "

- e (observed) $\simeq$ e (expected)
- μ (observed) < μ (expected)

$\downarrow$

- cannot be $\nu_\mu \to \nu_e$
- likely to be $\nu_\mu \to \nu_\tau$

$\downarrow$

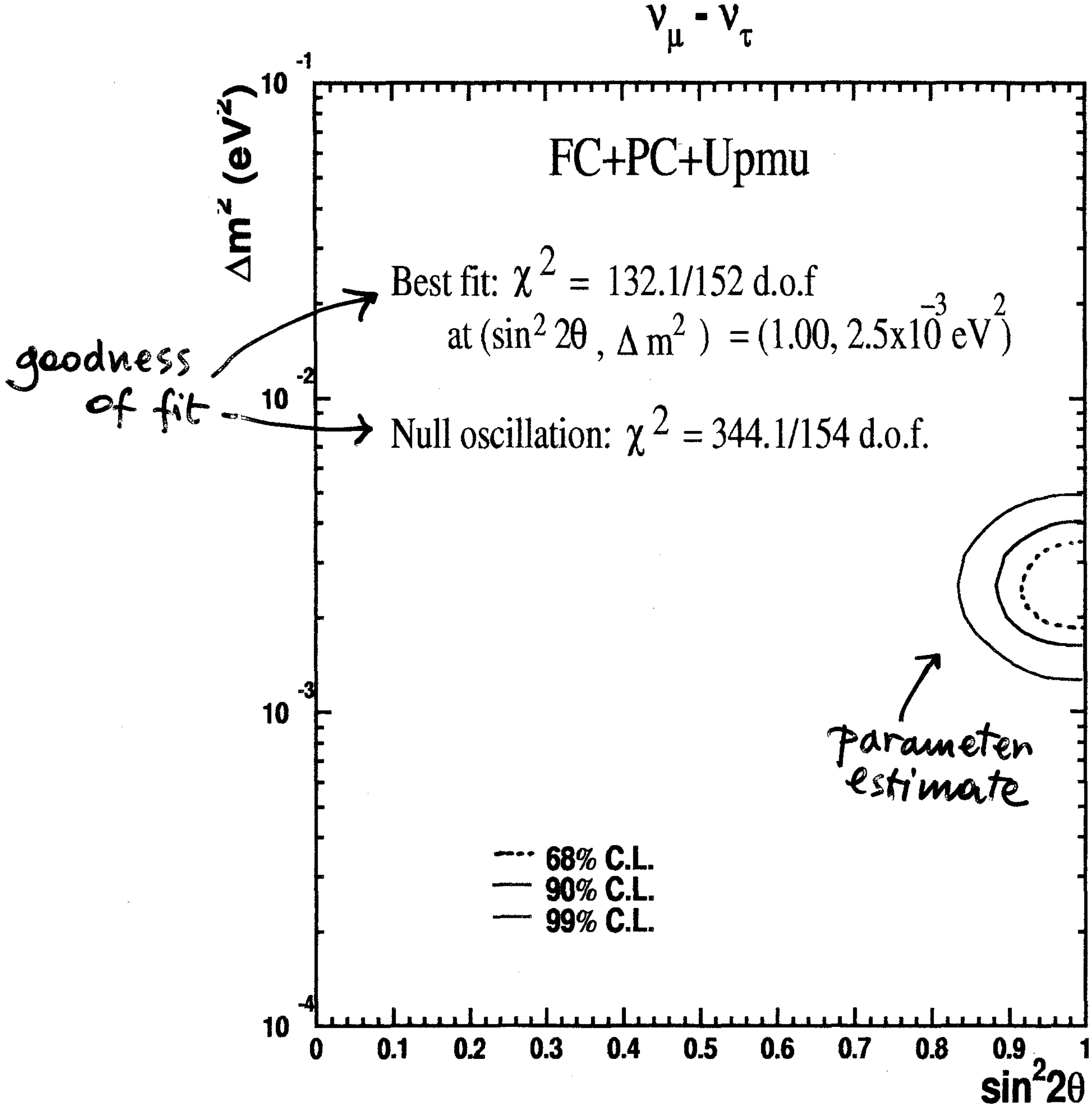
- if $\nu_\mu \to \nu_\tau$, then $\Delta V_{\mu\tau} = 0$ (vacuum-like)
- lots of spectral data $\left(\frac{dR_\mu}{dE}, \frac{dR_\mu}{d\theta_z}\right)$

$\downarrow$

$\nu_\mu \leftrightarrow \nu_\tau$ analysis expected to select a relatively small spot in mass-mixing param. space

Official SK analysis

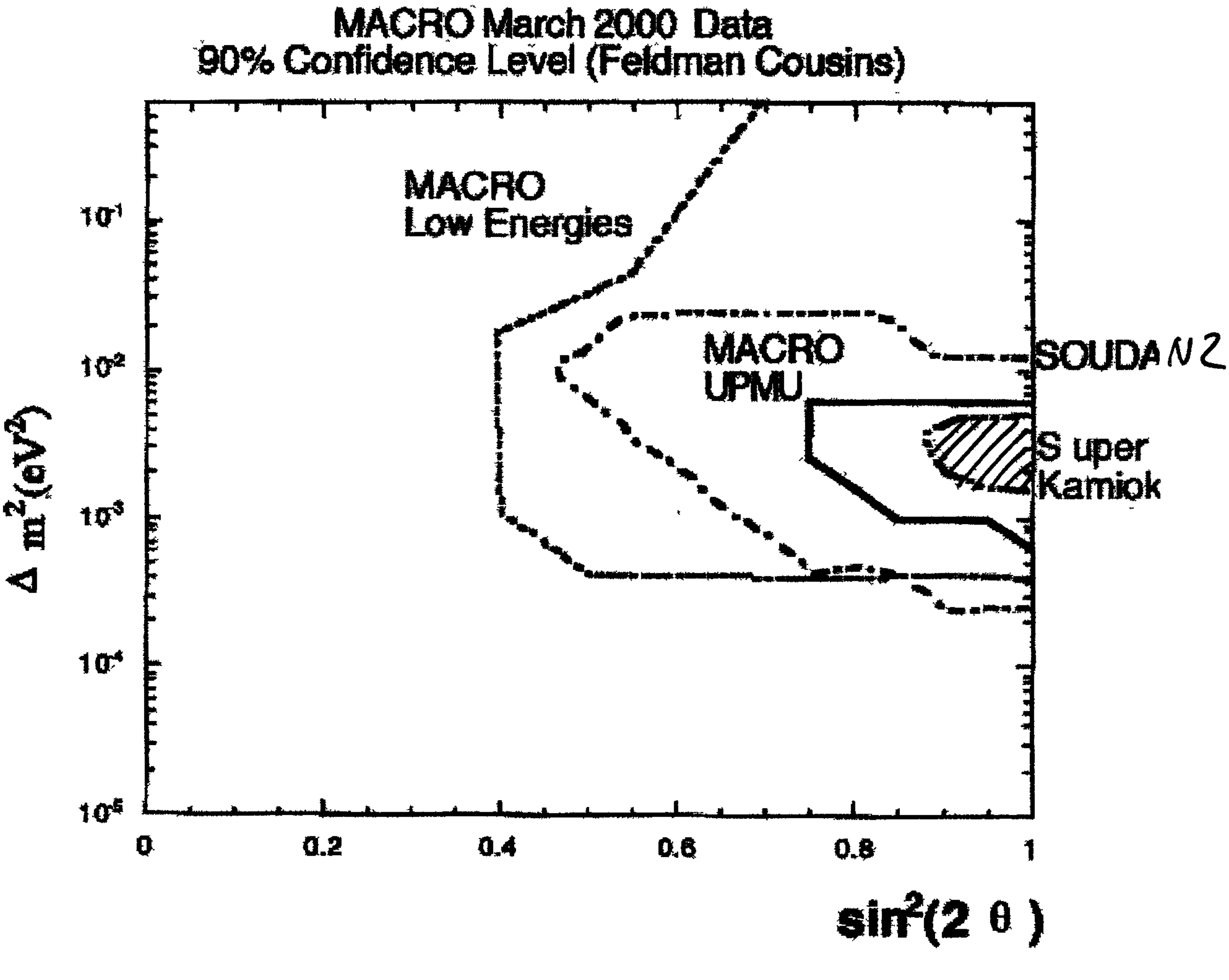
$\nu_\mu \leftrightarrow \nu_\tau$



Best fit: $\Delta m^2 \simeq 2.5 \times 10^{-3}\ eV^2$

$\sin^2 2\theta \simeq 1$ ("maximal mixing")

Confidence level regions
(ν_μ--> ν_τ oscillations)



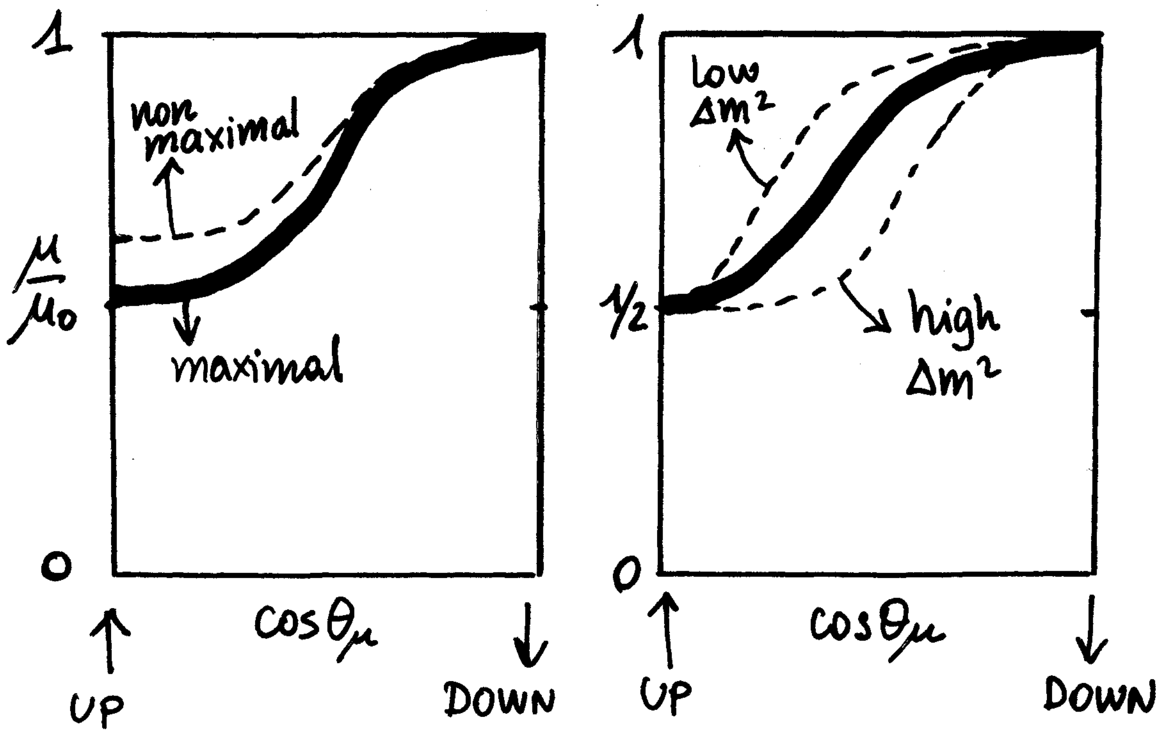
CONSISTENCY AMONG DIFFERENT EXPERIMENTS

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

$(\Delta m^2, \sin^2 2\theta)$ fit robust because:

- DIFFERENT SK DATA CONSISTENT WITH EACH OTHER
- DIFFERENT EXPERIMENTS CONSISTENT WITH EACH OTHER
- FIT DOMINATED BY A SINGLE, STRIKING EVIDENCE:
  U/D ASYMMETRY OF multi-GeV muons

multiGeV μ



... CANNOT CHANGE $\sin^2 2\theta$ TOO MUCH...

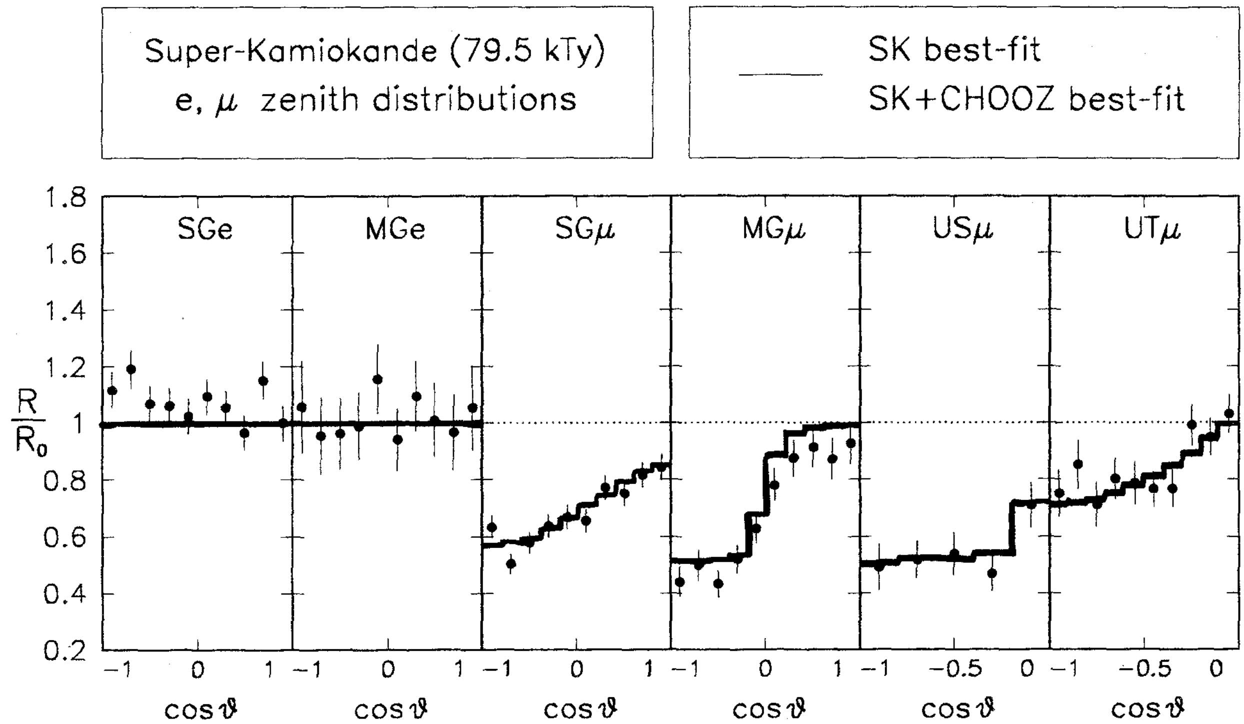
... CANNOT CHANGE Δm^2 TOO MUCH....

At best fit:

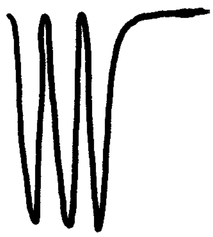
$P(\nu_\mu \to \nu_e) = 0 \qquad P(\nu_\mu \to \nu_\tau) \cong \sin^2\left(4 \frac{L/\mathrm{km}}{E/\mathrm{MeV}}\right)$

shown is $\int \phi \otimes P \otimes \sigma \otimes \epsilon_{ff}$

Fogli
E.L.
Marrone



$\nu_\mu \leftrightarrow \nu_\tau$



A "MIRACLE":

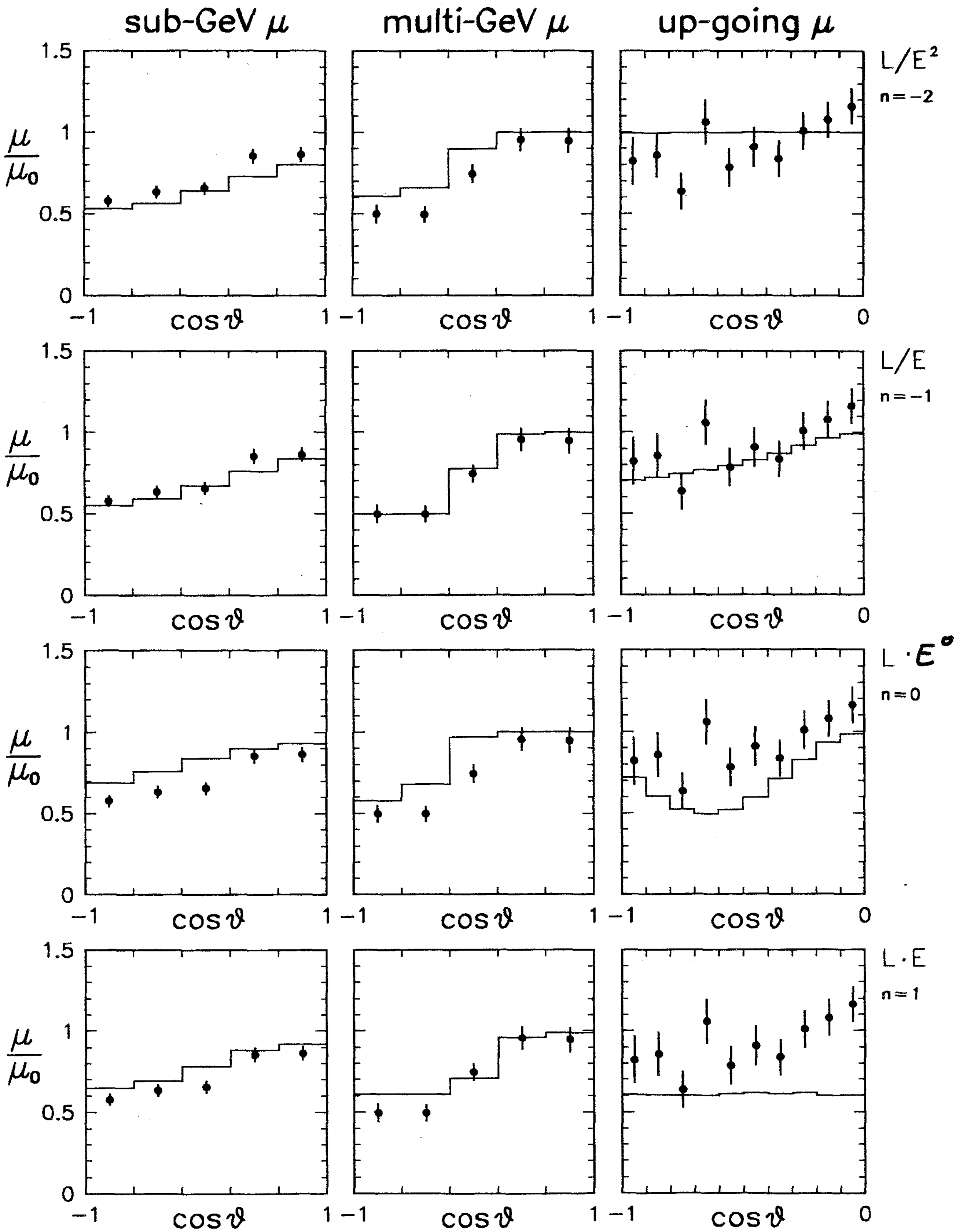
- Exceedingly simple formula for $P_{\mu\tau}$ works over 3 decades in L and 4 in E
- Nobody could have guessed <u>sin</u>^{2} form from the data without prior theory

MOREOVER,

$\sin^2$ argument <u>must</u> be $\propto L/E$ →

Super-Kamiokande muon distributions at best fit

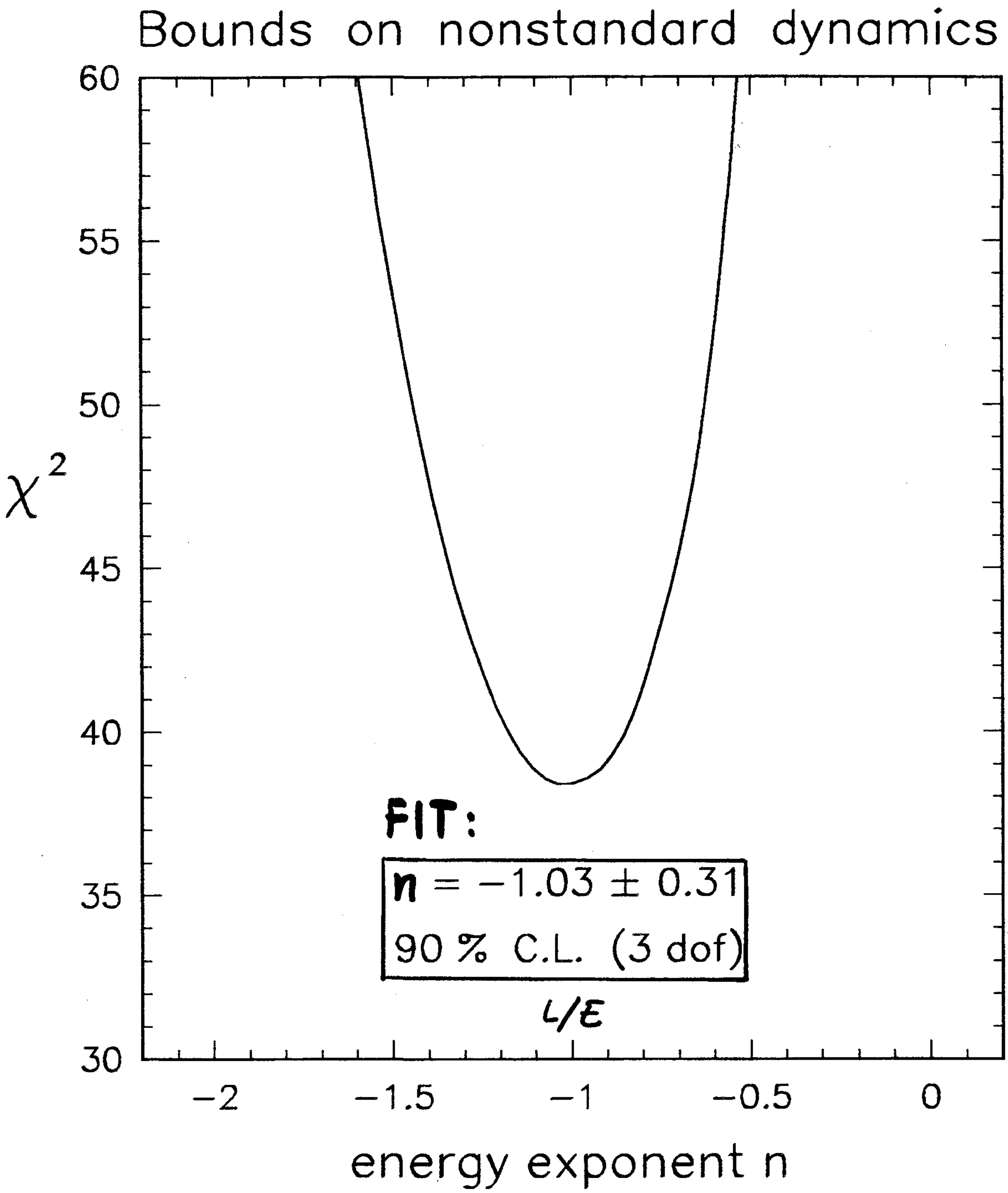
	L/E²	L/E	L	L•E
α →	1.00	1.00	0.51	0.78
β_2 →	3.00	3.56	0.19	0.27
χ^2 →	47.7	20.3	62.9	66.0



Only L/E gives good agreement at all L, E probed by SK

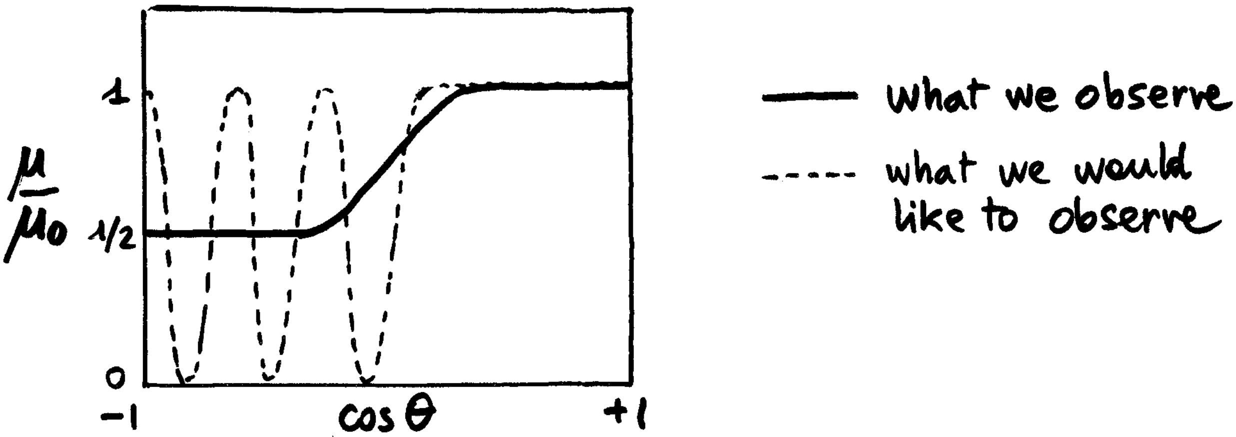
$P_{\mu\tau} = \alpha \sin^2(\beta\, L E^n)$ $n = -1 \rightarrow L/E$

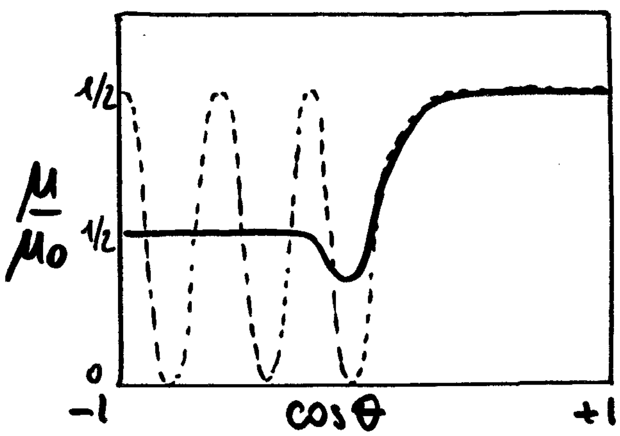
Fit with (α, β, n) free



(It was $n = -0.9 \pm 0.4$ with 45 kTy data)

$\nu_\mu \leftrightarrow \nu_\tau$ EXPLANATION :
- Theoretically SIMPLE
- Experimentally ROBUST
- .... but INDIRECT !





Future atmospheric ν experiments aim to see at least the first "disappearance dip"

LB experiments aim to detect ν_τ appearance

While waiting for future observations ...

... ROOM FOR SKEPTICISM:

SCENARIOS WITH NON PERIODIC $P_{\mu\mu}(L/E)$

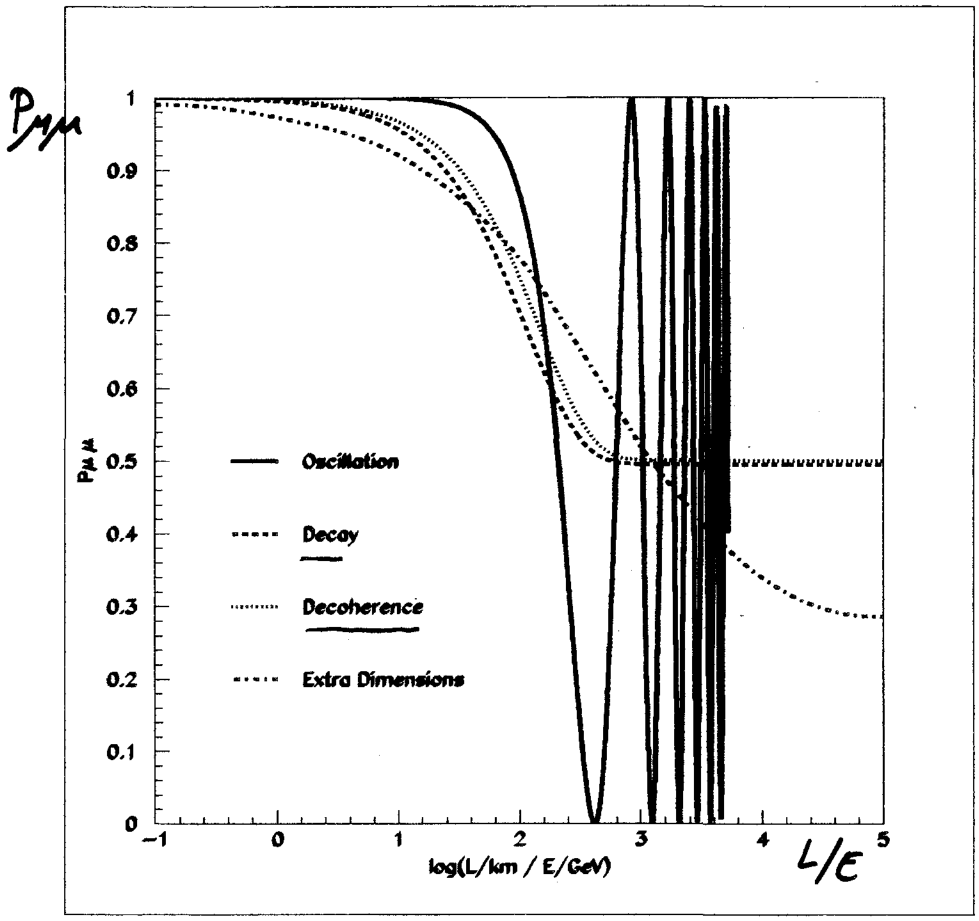


FIGURE 1. Survival probality for ν_μ versus log_{10} (L/E) for the decay model, decoherence, extra dimensions and oscillation.

STILL ~ COMPATIBLE WITH DATA

BUT PARAMETERS RATHER "AD HOC"

11

ATMOSPHERIC ν:

$\nu_\mu \leftrightarrow \nu_\tau$ OK

... BUT:

OSCILLATION PATTERN
NOT YET OBSERVED

WE'LL SHOW NOW THAT

$\nu_\mu \leftrightarrow \nu_s$ disfavored

- HERE, MATTER EFFECTS IMPORTANT ($V_\mu(x) - V_s(x) \neq 0$) BUT NOT OBSERVED!

Remember:

For $\nu_\mu \leftrightarrow \nu_\tau$: $\mathcal{H} = \mathcal{H}_{vacuum}$ (mod 1)

For $\nu_\mu \leftrightarrow \nu_s$: $\mathcal{H} = \mathcal{H}_{vacuum} + \begin{pmatrix} \Delta V & 0 \\ 0 & 0 \end{pmatrix}$

$\Delta V = V_\mu - V_s \neq 0$

$\downarrow$

effective mixing angle in matter : $$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left(\frac{2\Delta V \cdot E}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

- **MSW** effect mostly known for the possible enhancement of small vacuum mixing:

$\sin^2 2\theta$ small $\longrightarrow \sin^2 2\theta_m \sim 1$ for $\Delta V \sim \Delta m^2/2E$

- BUT HERE WE ARE INTERESTED IN THE OPPOSITE FACT:

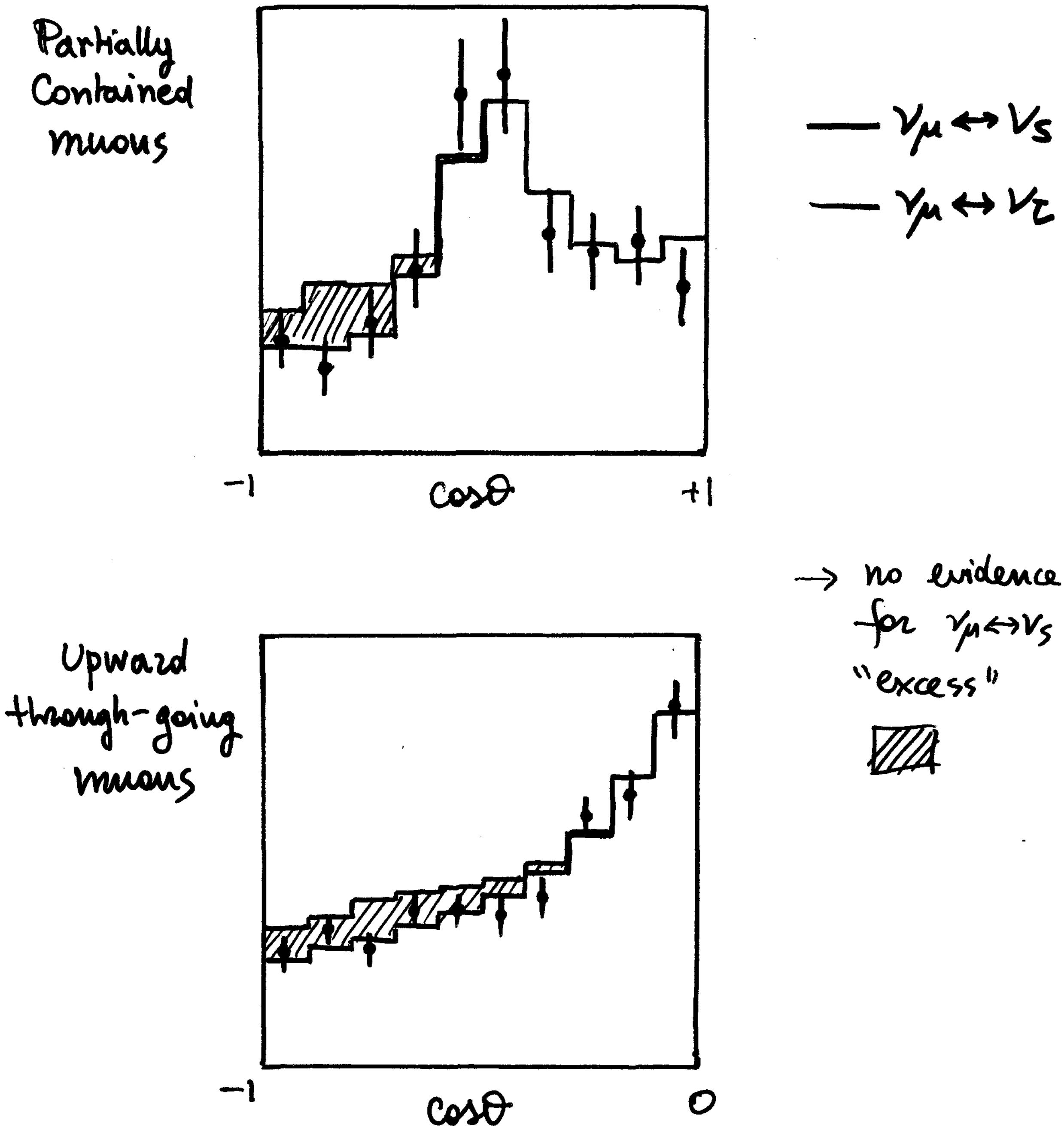
$$\sin^2 2\theta \simeq 1 \longrightarrow \sin^2 2\theta_m \simeq \frac{1}{1 + \left(\frac{2\Delta V \cdot E}{\Delta m^2}\right)^2} < 1$$

↑ ESPECIALLY AT HIGH E

→ matter effects inhibit atmospheric ν_μ disappearance if $\nu_\mu \to \nu_s$

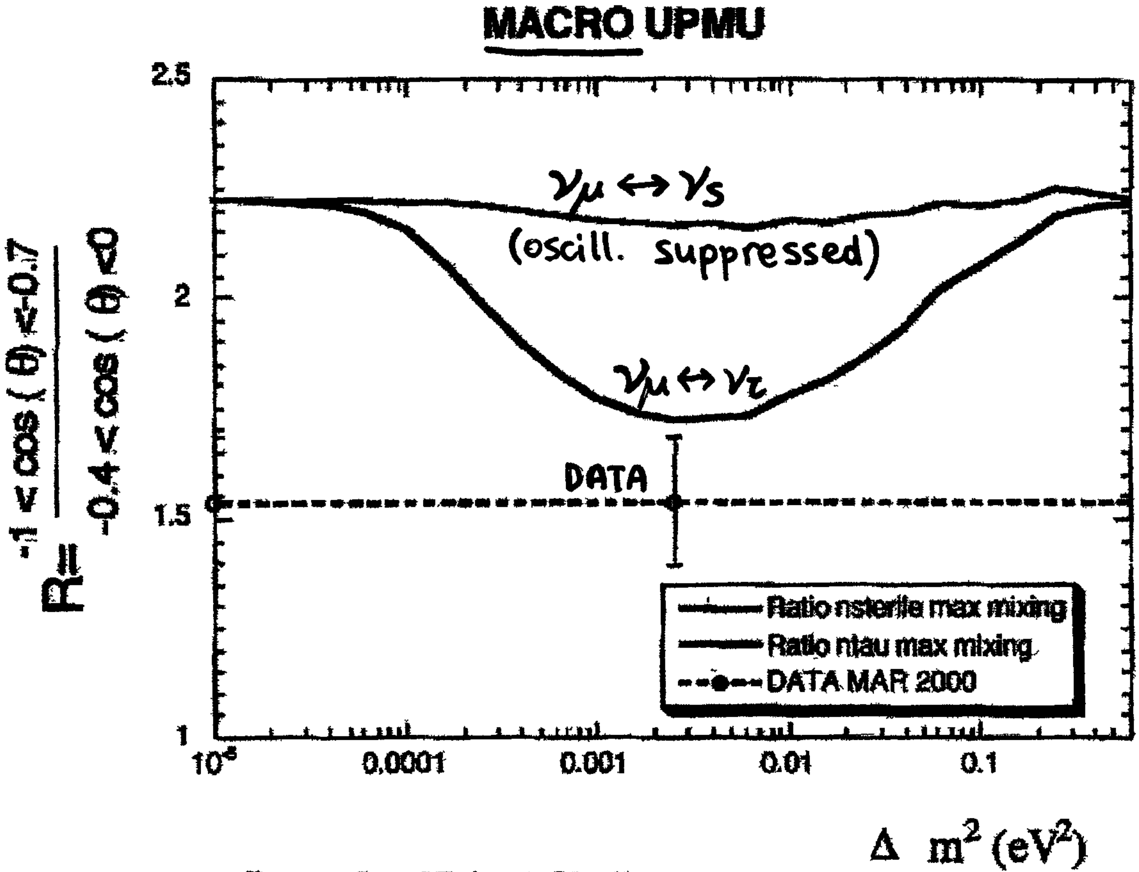
BUT: SK DATA DO NOT SUPPORT $\sin^2 2\theta_m < 1$

→ High-energy muons in SK



SK claim: $\nu_\mu \leftrightarrow \nu_s$ DISFAVORED @ >99% C.L.

Ratio vertical/horizontal Montecarlo Optimized



P best Tau/ P best Sterile =
70 (5% systematic in each bin)
413 (no systematic error)

- **The plot is for** Maximum mixing.
- **Sterile neutrino disfavored respect to tau at >98% for any mixing** (5% systematic in each bin)

SEVERAL INDEPENDENT DATA SETS & ANALYSES DO NOT SUPPORT $\nu_\mu \to \nu_s$ AND THE ASSOCIATED (MATTER) EFFECTS

E.g. : no observation of reduced NC events (statistical) due to ν_s - non interacting

RECENTLY, SK CLAIMS ISOLATION OF "τ- like" "RINGS" AT THE 2σ LEVEL → FURTHER INDICATION AGAINST $\nu_\mu \to \nu_s$

↓

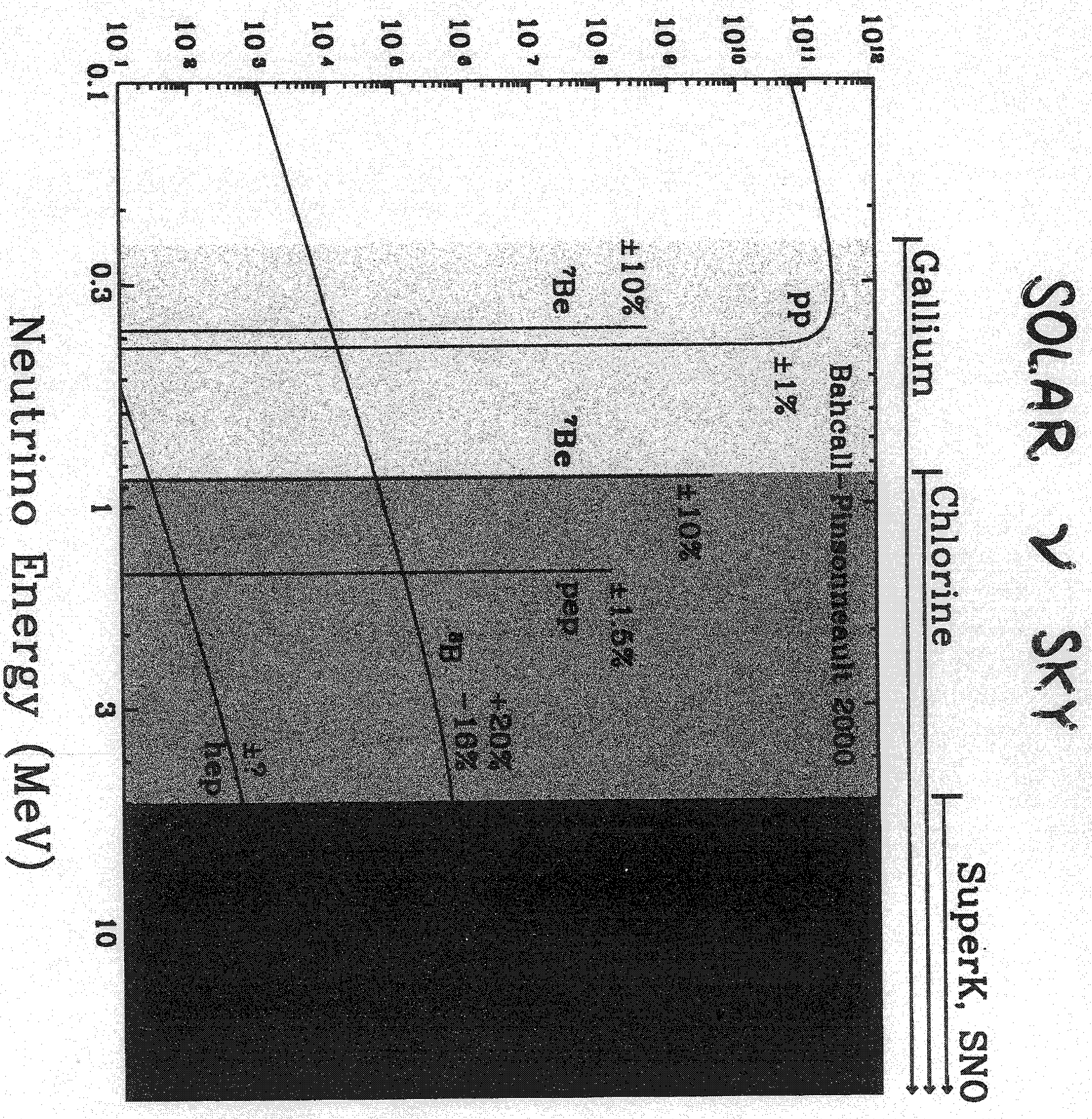
Sk data "don't like" ν_s at > 99% C.L.

(assuming PURE $\nu_\mu \to \nu_s$)

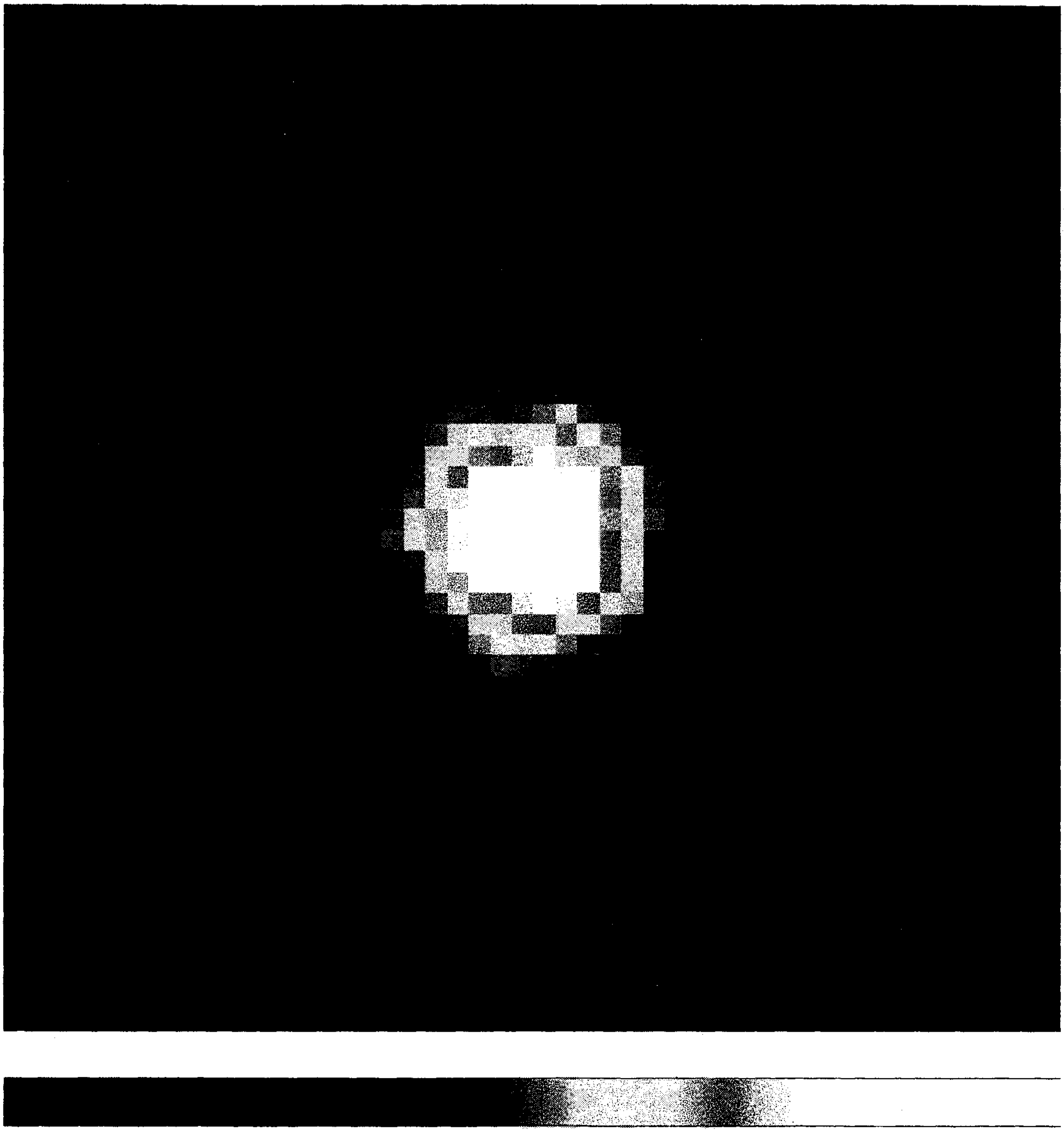
SOLAR ν:
pre-SNO situation

.... WAIT FOR LECTURE V
TO SEE S.N.O. effect....

Neutrino Flux



THE SUN
AS SEEN WITH ν'S

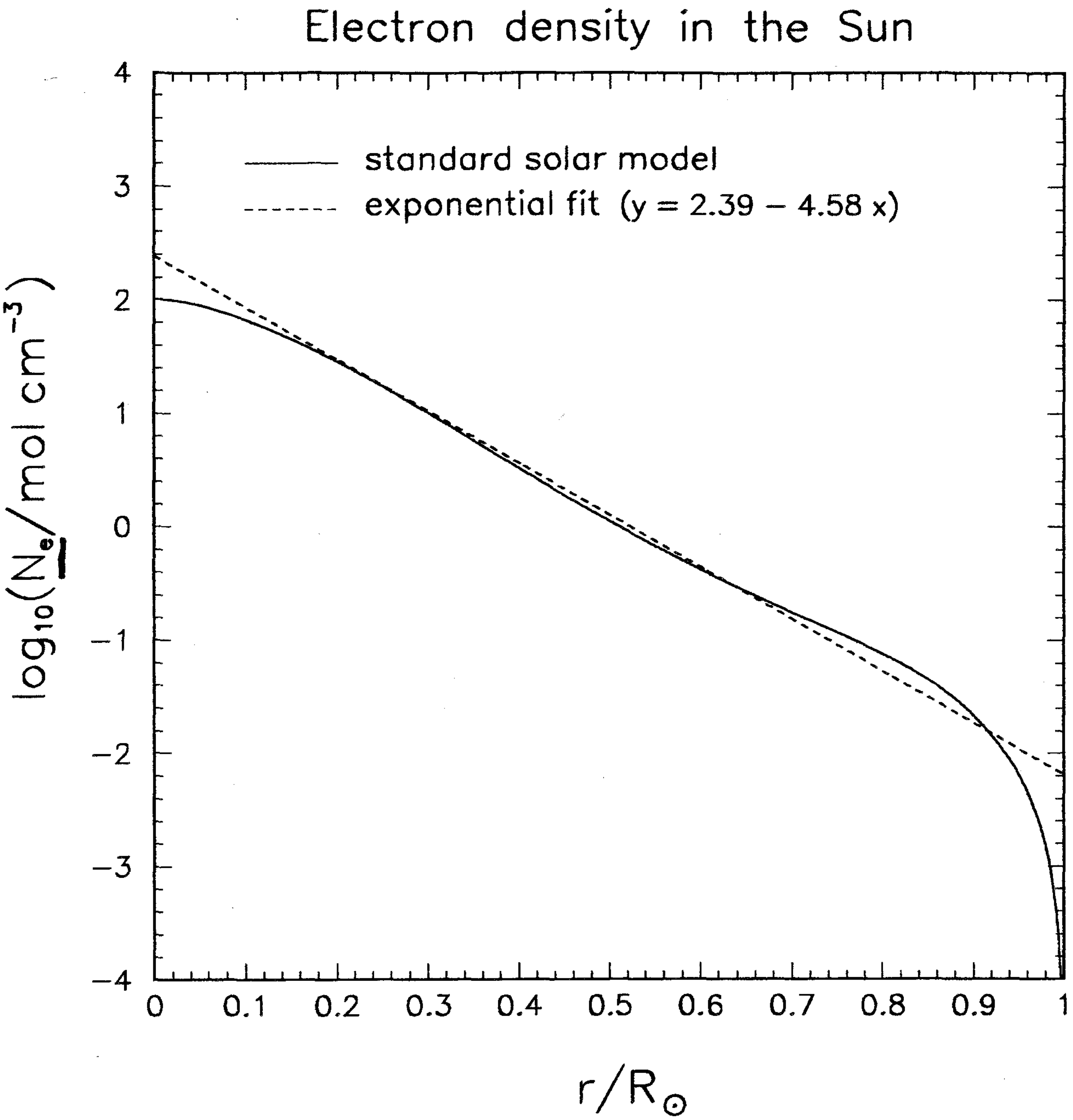


(SK)

SOLAR NEUTRINOS

EXPERIMENT	REACTION	
• Homestake	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	
• SAGE GALLEX + GNO	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge^* + e^-$	
• Kamiokande SuperKamiokande	$\nu_{e\mu\tau} + e \rightarrow \nu_{e\mu\tau} + e$	
• SNO [CC]	$\nu_e d \rightarrow p p e^-$	done! (in ~~progress~~)
• SNO [NC]	$\nu_{e\mu\tau} d \rightarrow p n \nu_{e\mu\tau}$	(near future)
.....		

- can probe ν_e disappearance over many orders of magnitude
- matter effects important in a large fraction of parameter space

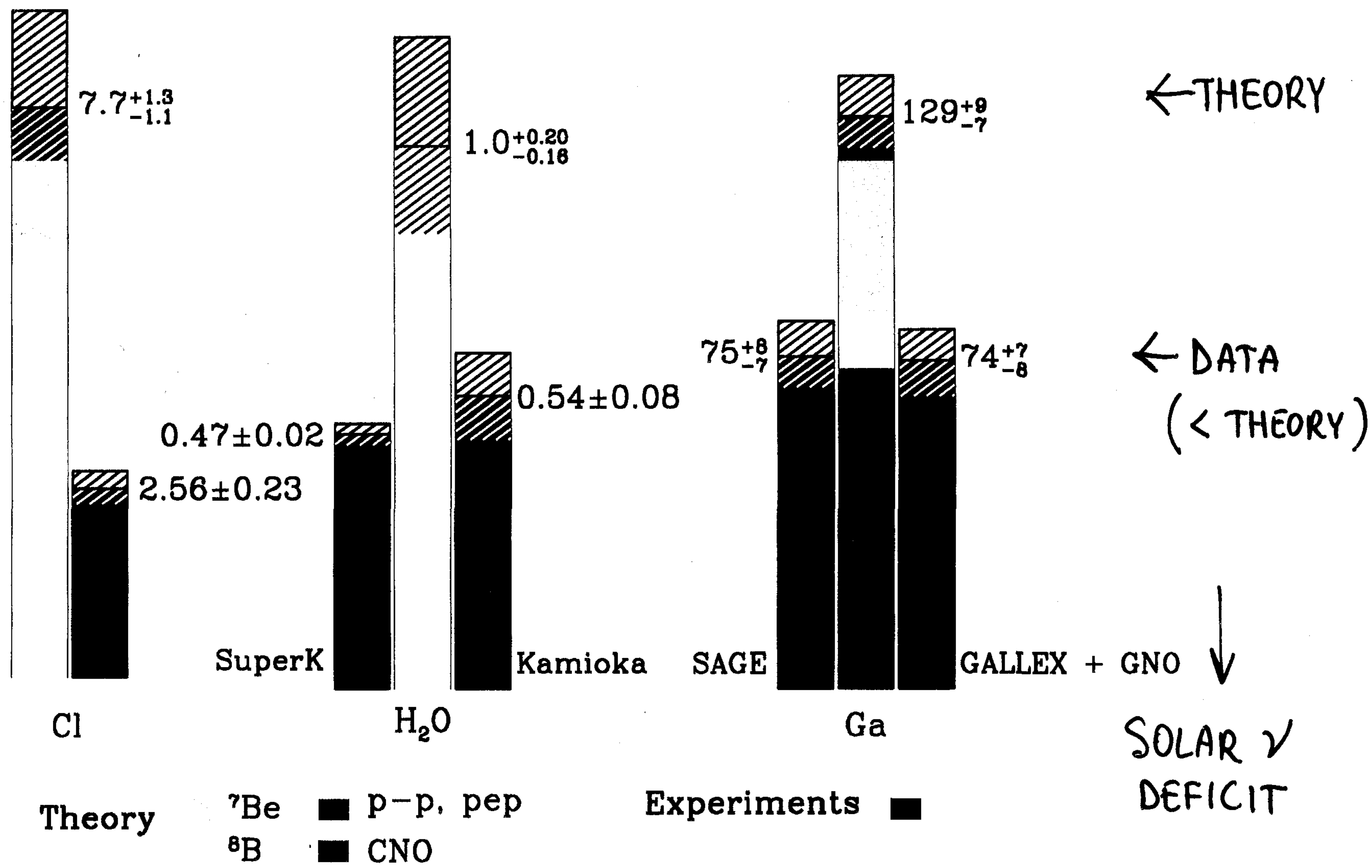


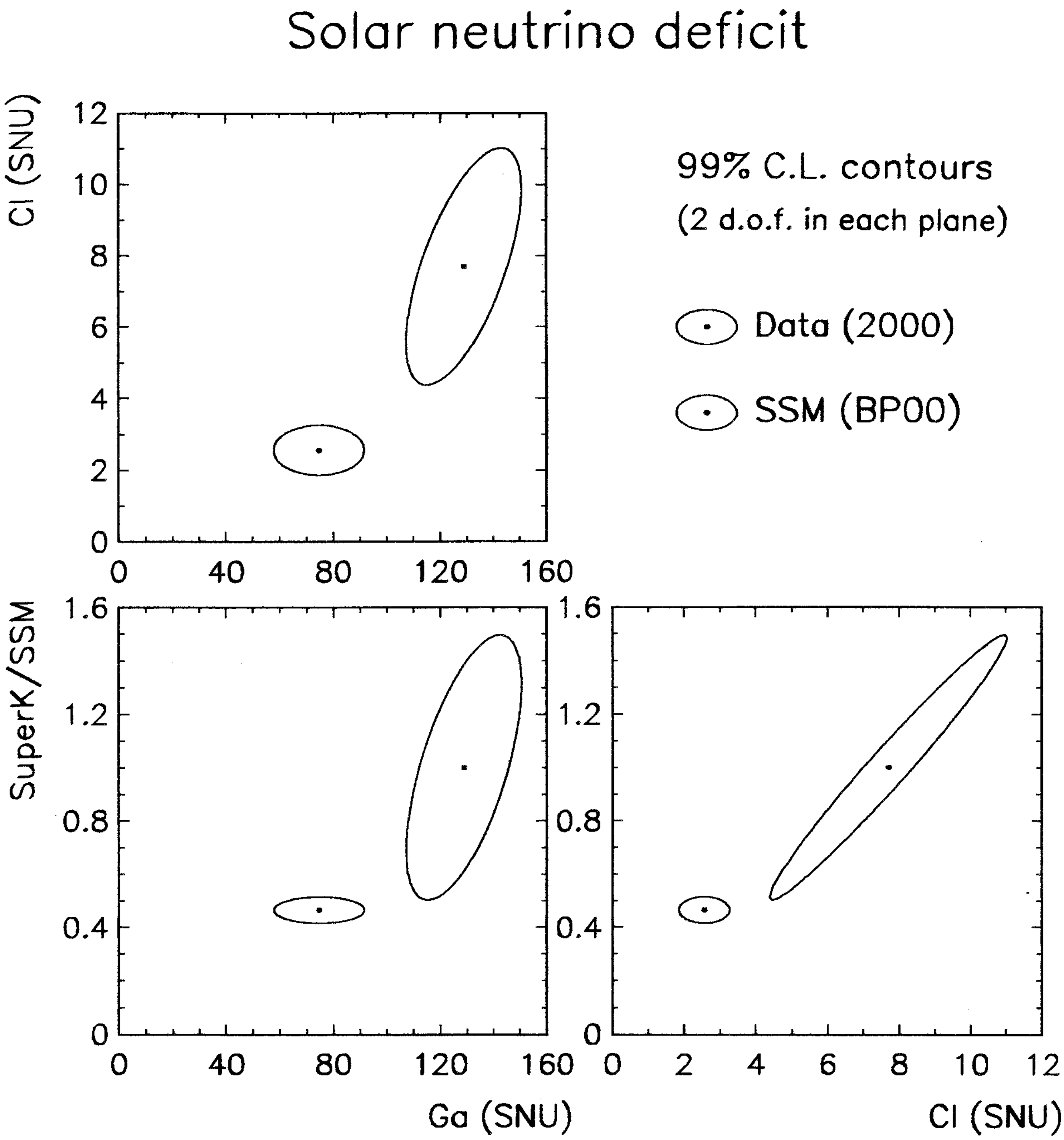
4 orders of magnitude in N_e

→ N_e relevant for
$\Delta m^2 \sim 10^{-8} \div 10^{-4}\ eV^2$

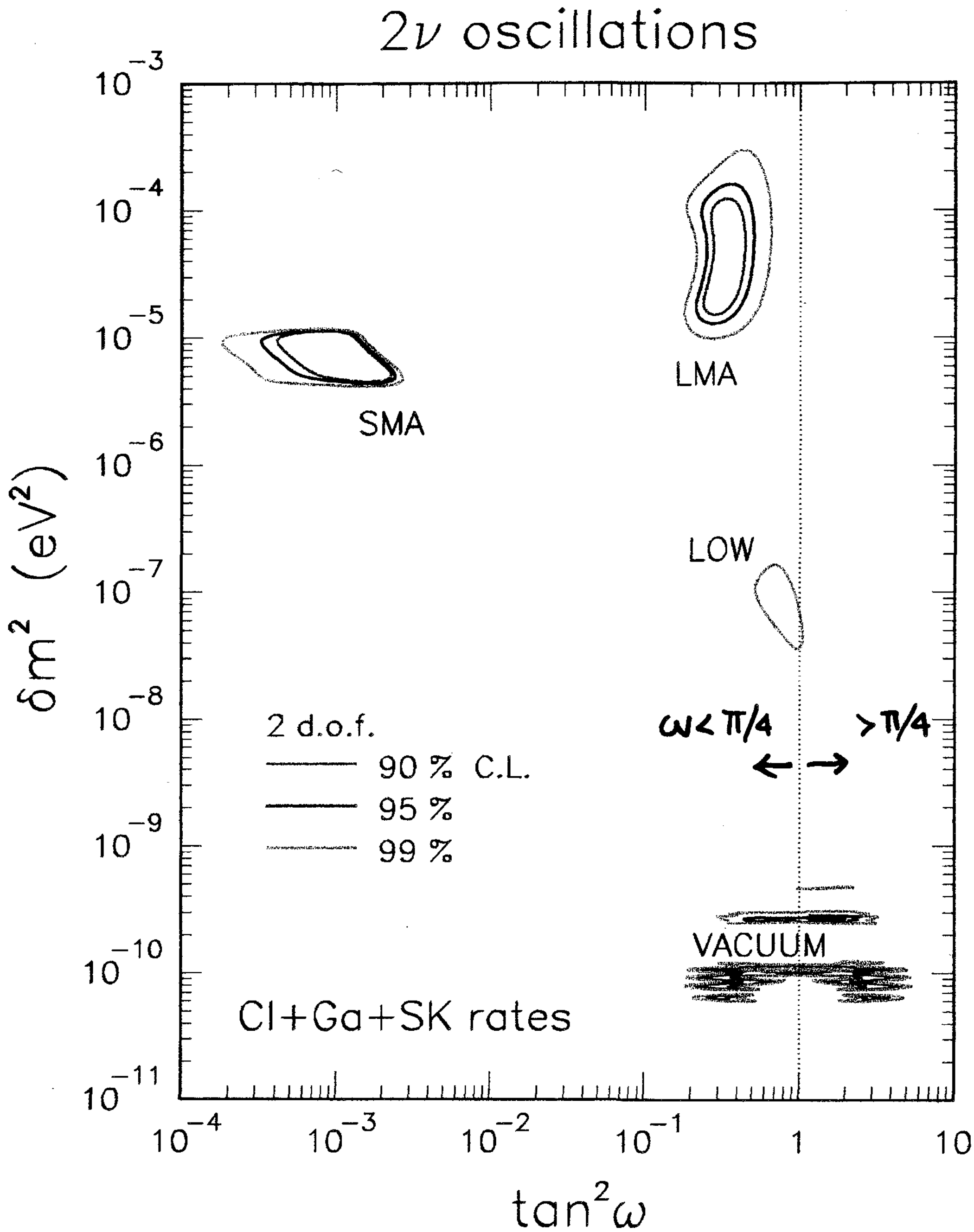
Total Rates: Standard Model vs. Experiment

Bahcall–Pinsonneault 2000



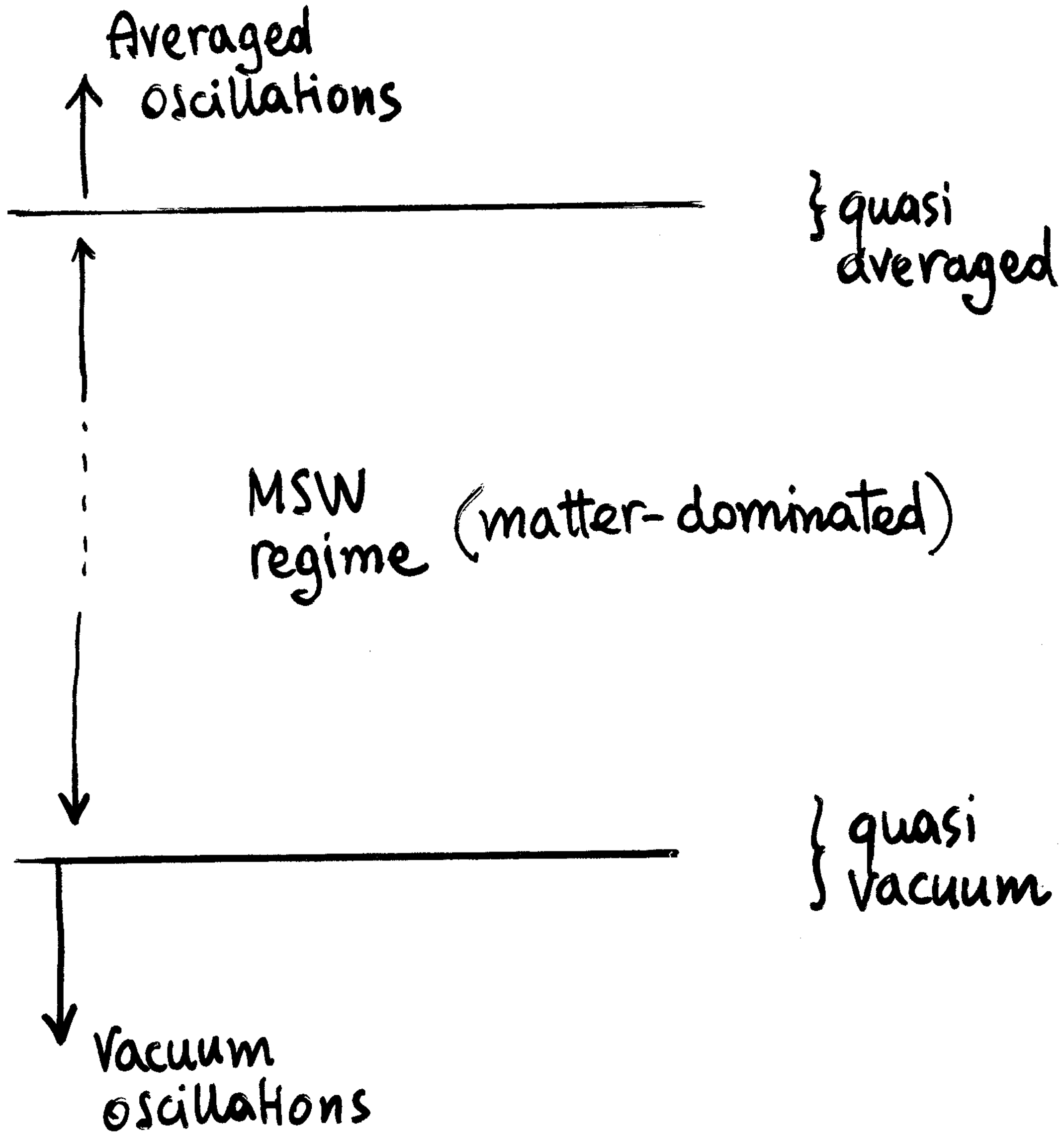

Solar neutrino deficit
99% C.L. contours
(2 d.o.f. in each plane)
Data (2000)
SSM (BP00)
Cl (SNU)
SuperK/SSM
Ga (SNU)
Cl (SNU)

Fogli, E.L.,
Montanino, Palazzo



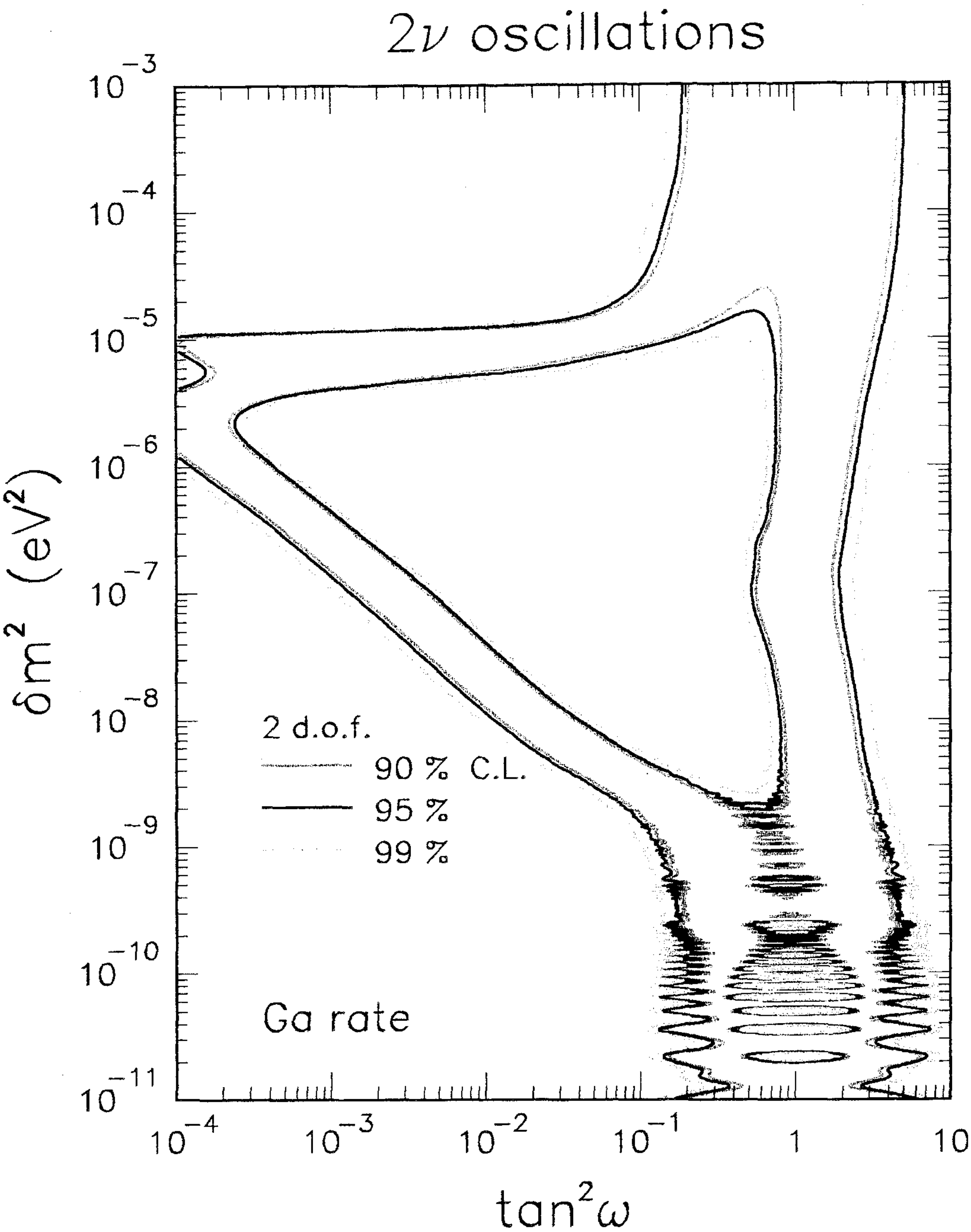
$\nu_e \rightarrow \nu_{\mu,\tau}$

- RATE INFORMATION ONLY
- 2000 DATA + Solar model

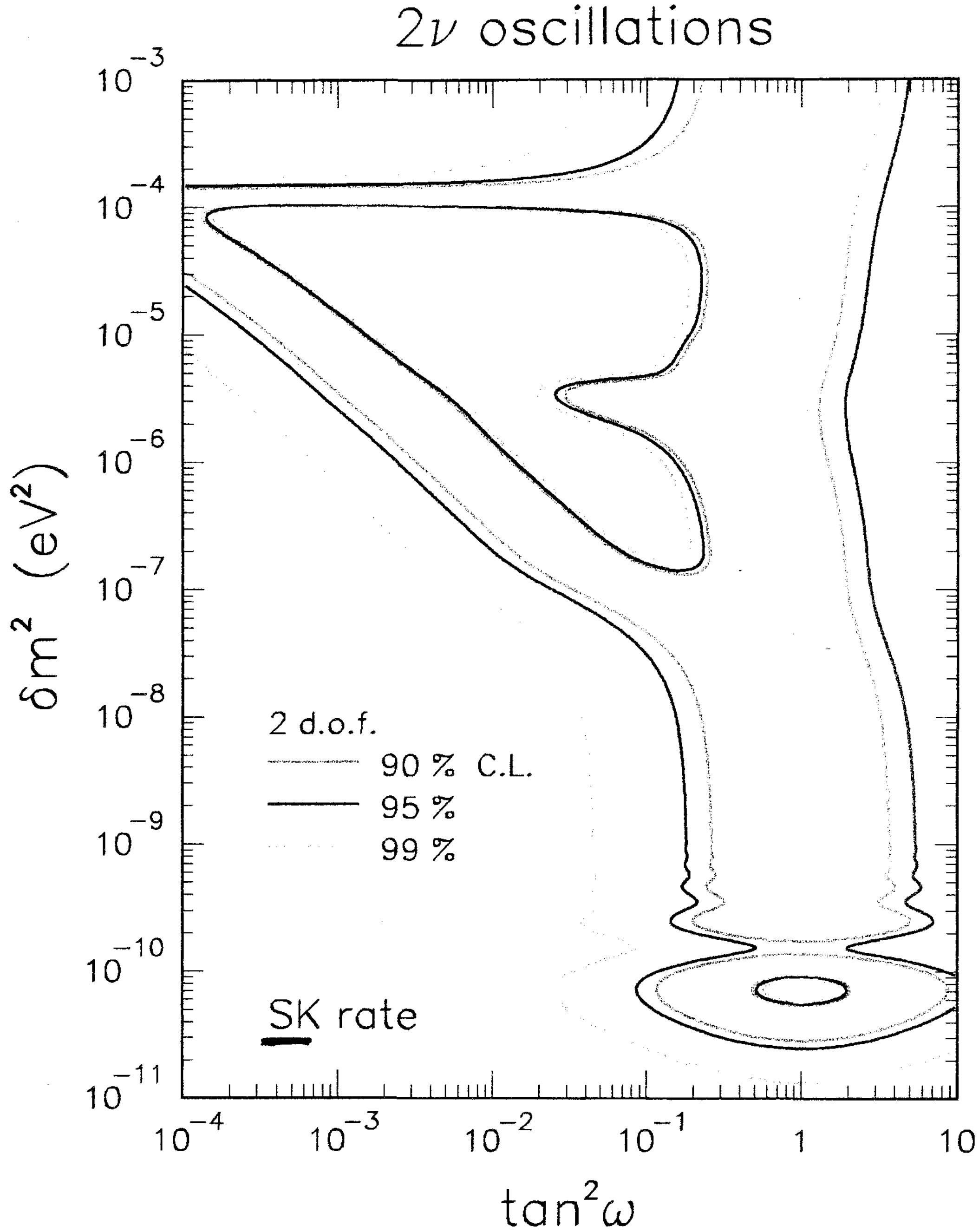


Rather different physics in different regimes

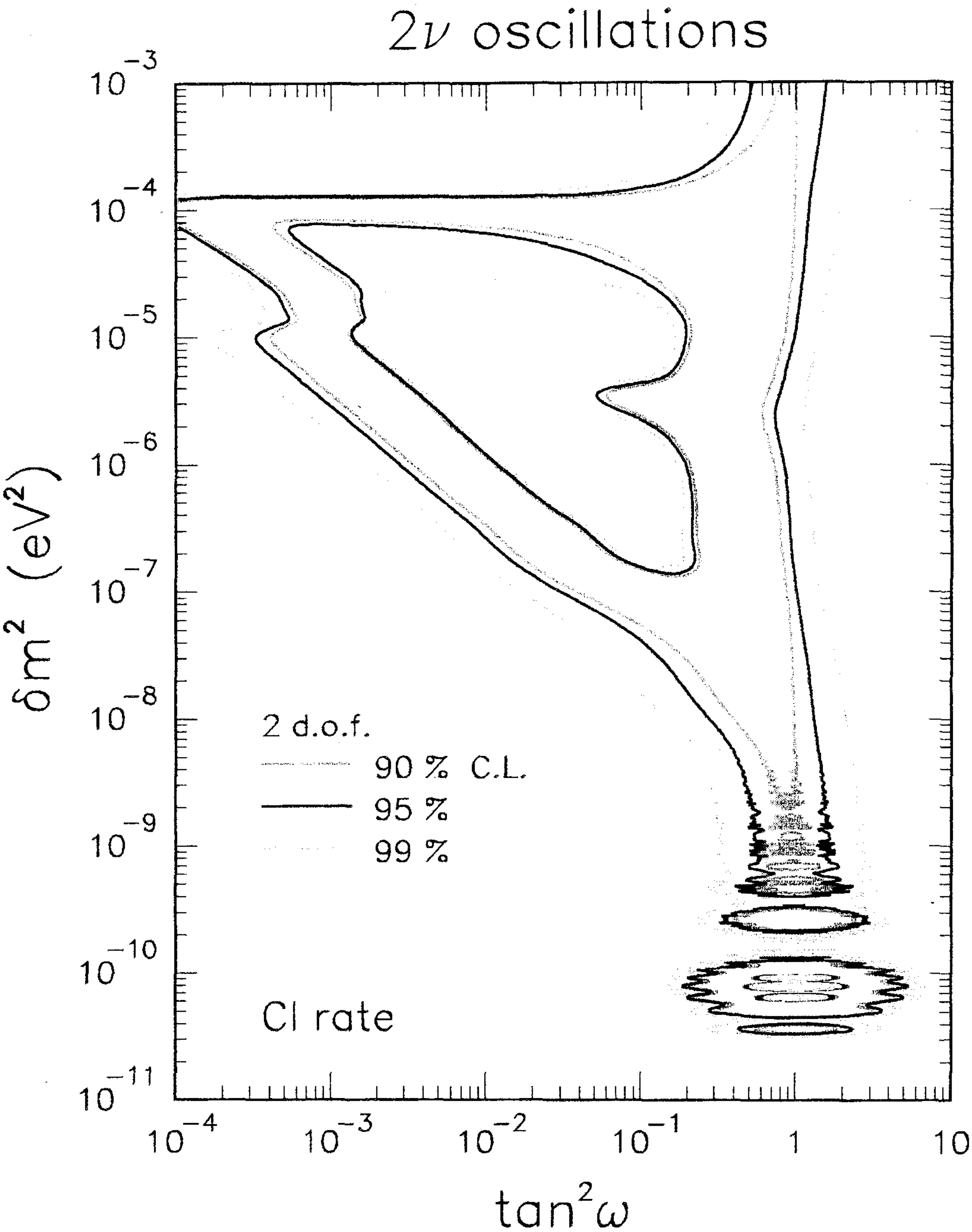
→ BREAK DOWN TO SINGLE EXPERIMENTS



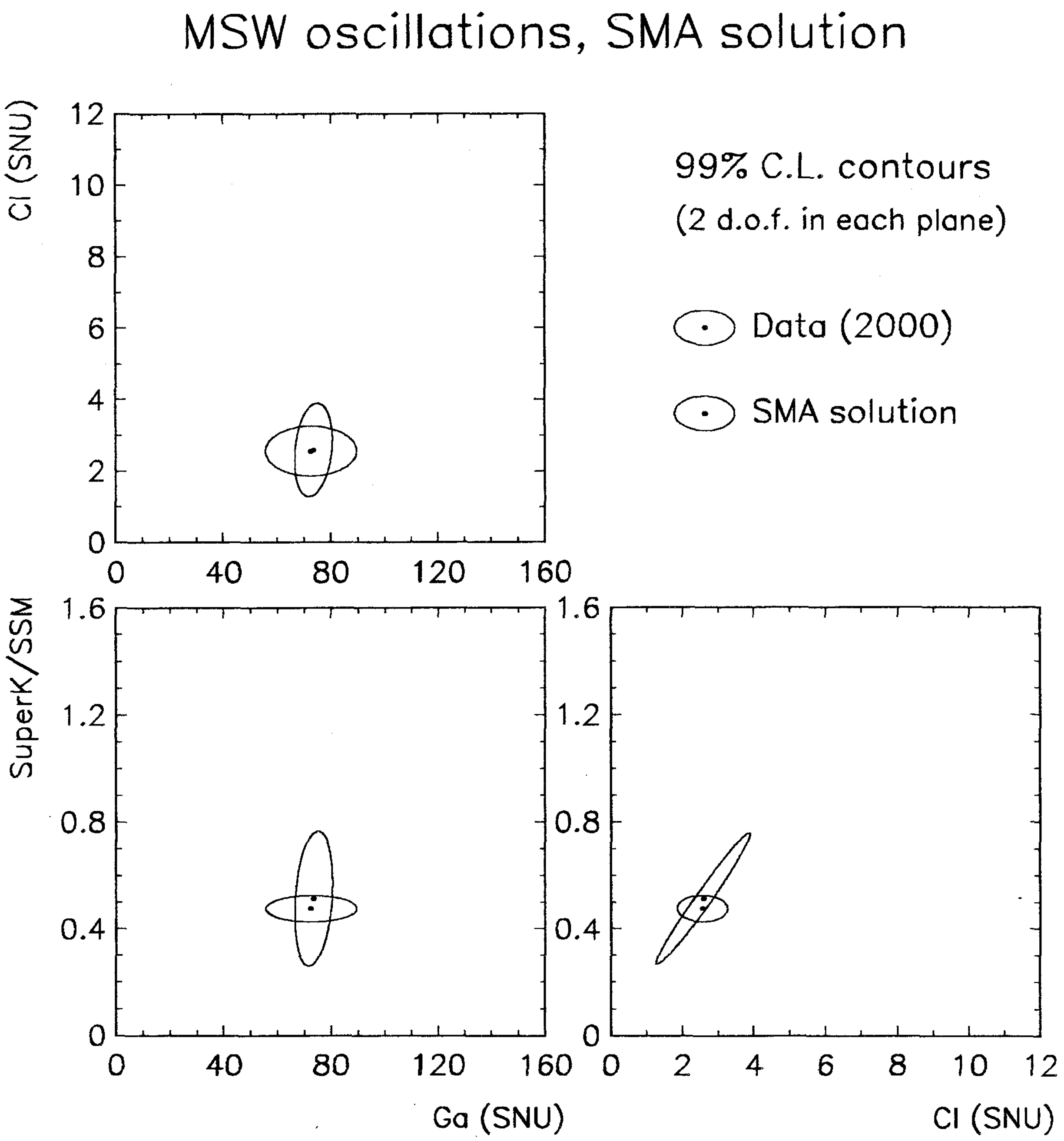
2ν oscillations
δm² (eV²)
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
2 d.o.f.
90 % C.L.
95 %
99 %
Ga rate
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
tan²ω



2ν oscillations
δm² (eV²)
tan²ω
2 d.o.f.
90 % C.L.
95 %
99 %
SK rate
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-4
10^-3
10^-2
10^-1
1
10

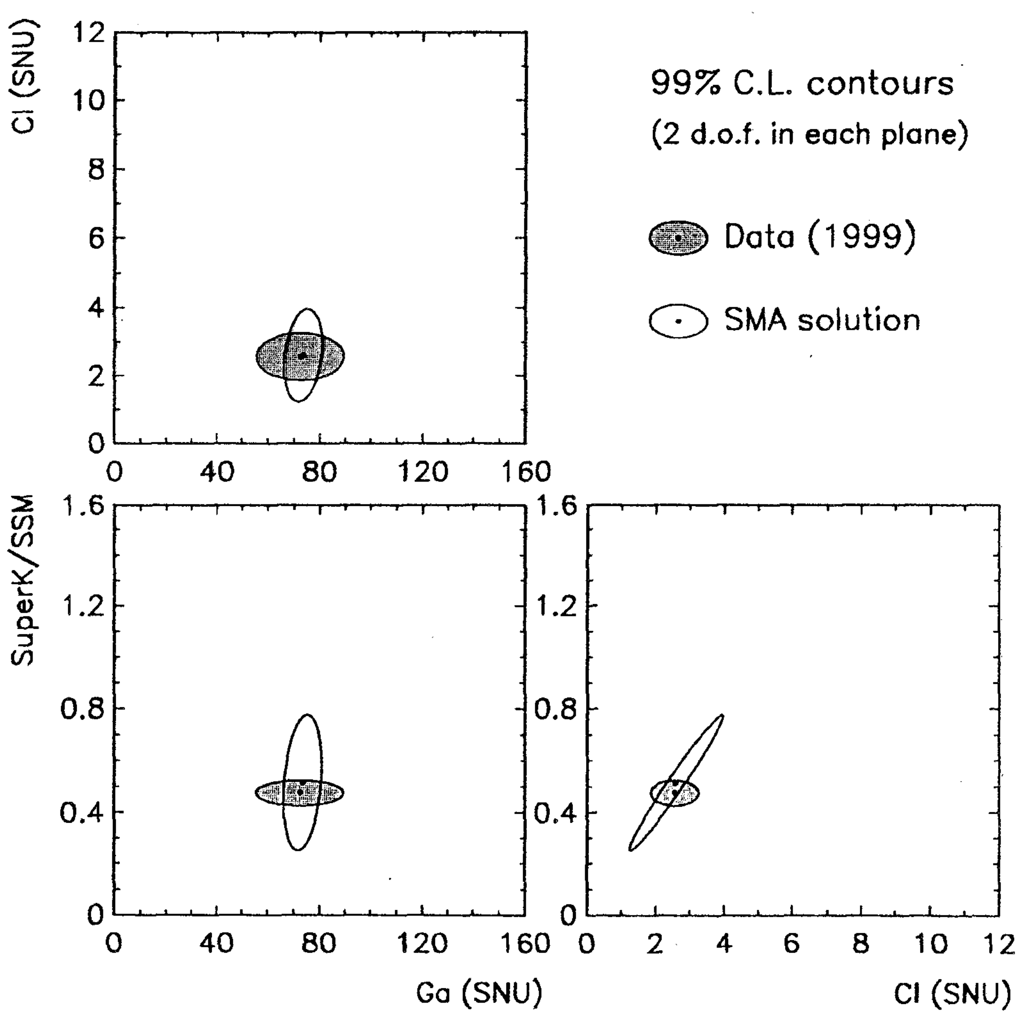


2ν oscillations
δm² (eV²)
tan²ω
2 d.o.f.
90 % C.L.
95 %
99 %
Cl rate

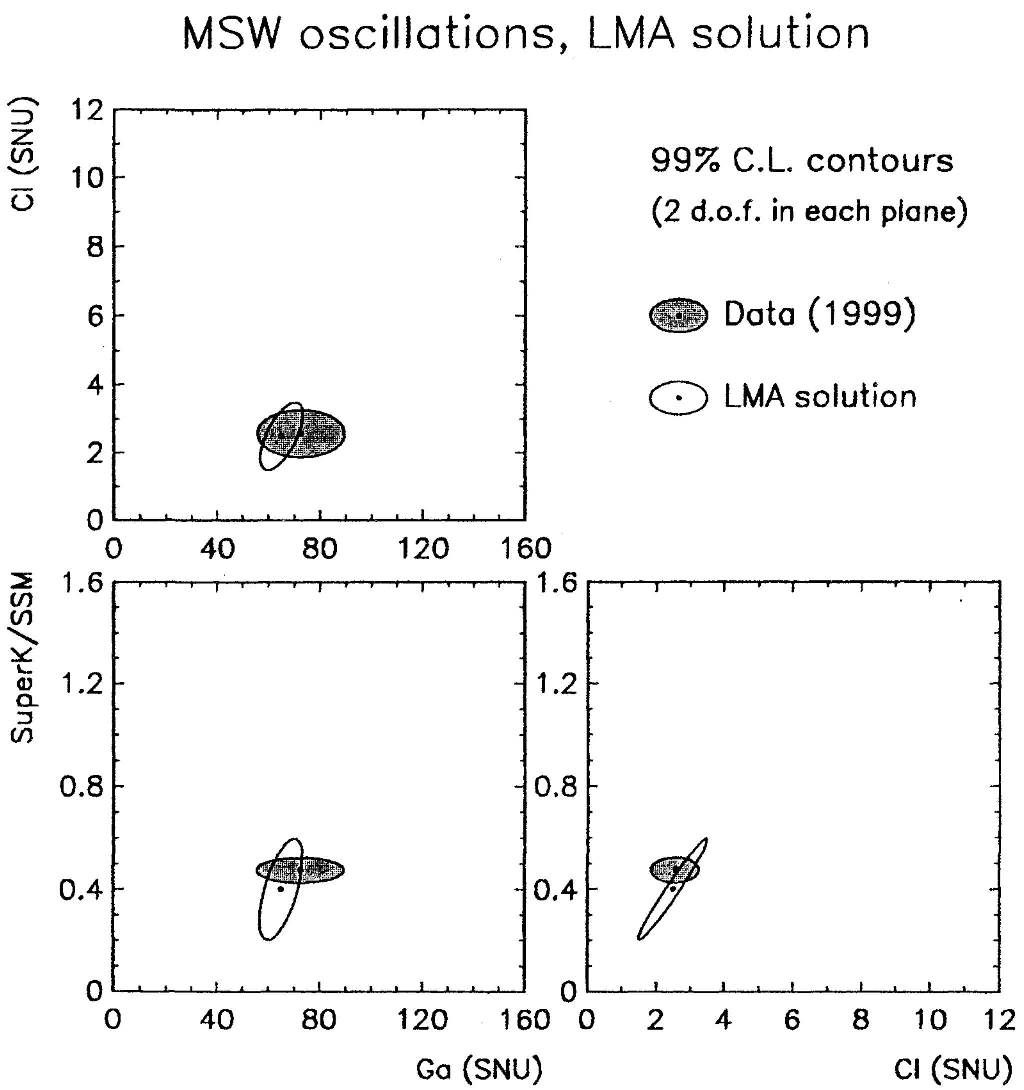

MSW oscillations, SMA solution
99% C.L. contours
(2 d.o.f. in each plane)
Data (2000)
SMA solution
Cl (SNU)
SuperK/SSM
Ga (SNU)
Cl (SNU)
12
10
8
6
4
2
0
40
80
120
160
1.6
1.2
0.8
0.4

- SMA provides perfect fit to rates
- Both LMA and LOW underestimate Ga
- LOW overestimates Cl

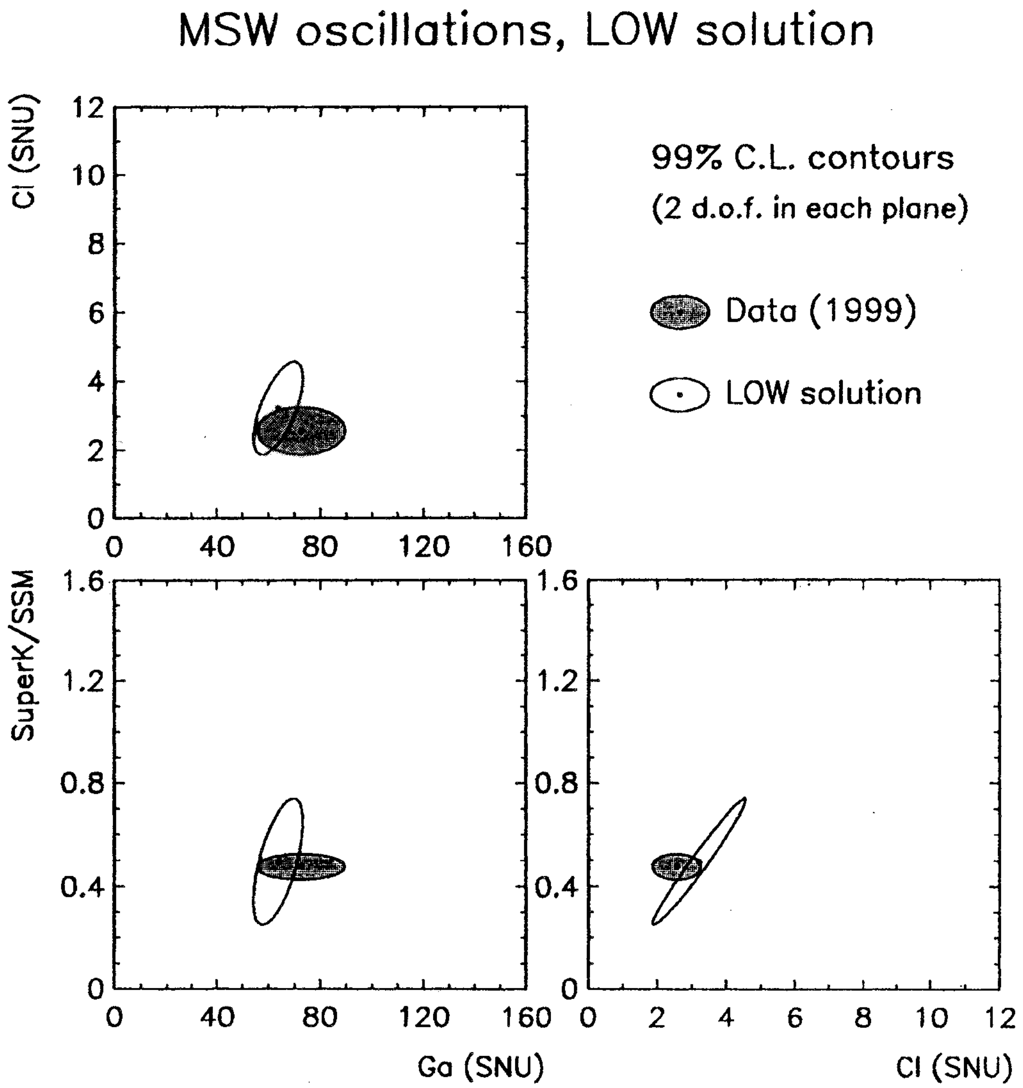
MSW oscillations, SMA solution



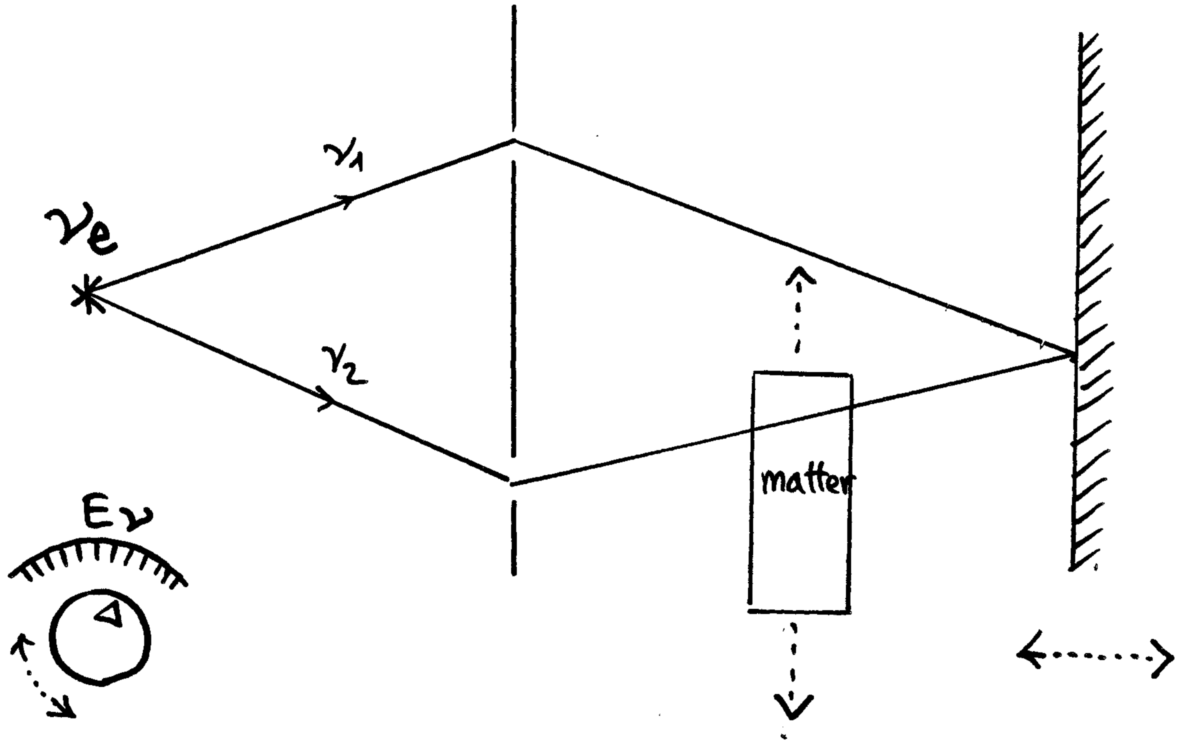
However, bulk of SK/SSM spectrum is flat (as predicted by LOW and LMA solutions) while a "tilt" is expected for the SMA solution (see later)



MSW oscillations, LMA solution
99% C.L. contours
(2 d.o.f. in each plane)
Data (1999)
LMA solution
Cl (SNU)
SuperK/SSM
Ga (SNU)
Cl (SNU)


MSW oscillations, LOW solution
99% C.L. contours
(2 d.o.f. in each plane)
Data (1999)
LOW solution
Cl (SNU)
SuperK/SSM
Ga (SNU)
Cl (SNU)

AVERAGE DEFICIT ↔ "GREY SCREEN"
HOW TO GET MORE INFORMATION ?



"TUNE" ENERGY → energy spectrum

"MOVE" MATTER IN AND OUT → day-night earth effect

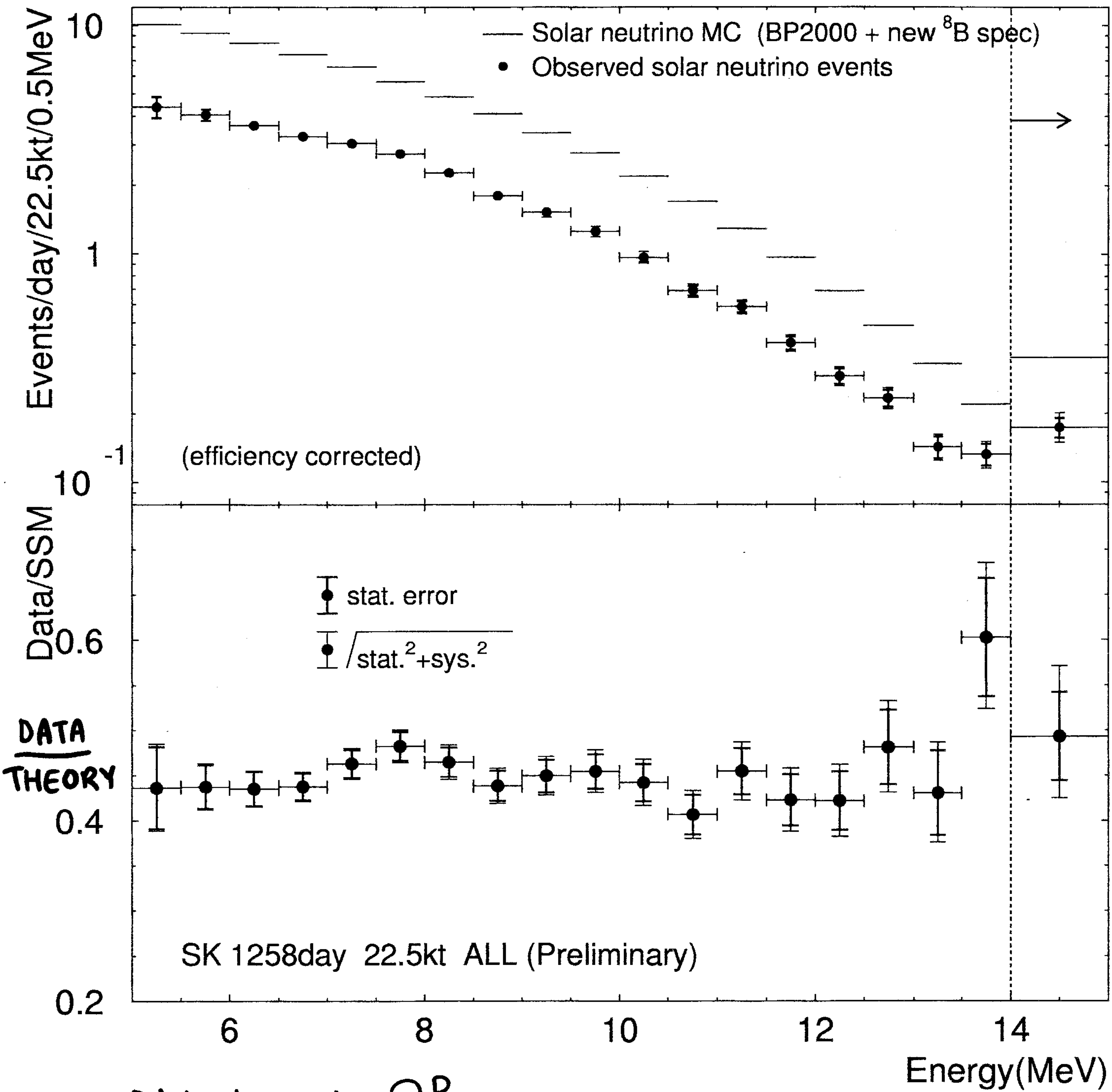
"MOVE" SCREEN BACK AND FORTH → eccentricity variations of L

→ HOPE TO "ENHANCE" INTERFERENCE PATTERN

SK 2001

The Recoil Spectrum

$\nu + e \rightarrow \nu + \boxed{e}$-spectrum



Distortion if $\frac{\partial P_{ee}}{\partial E_\nu} \neq 0$

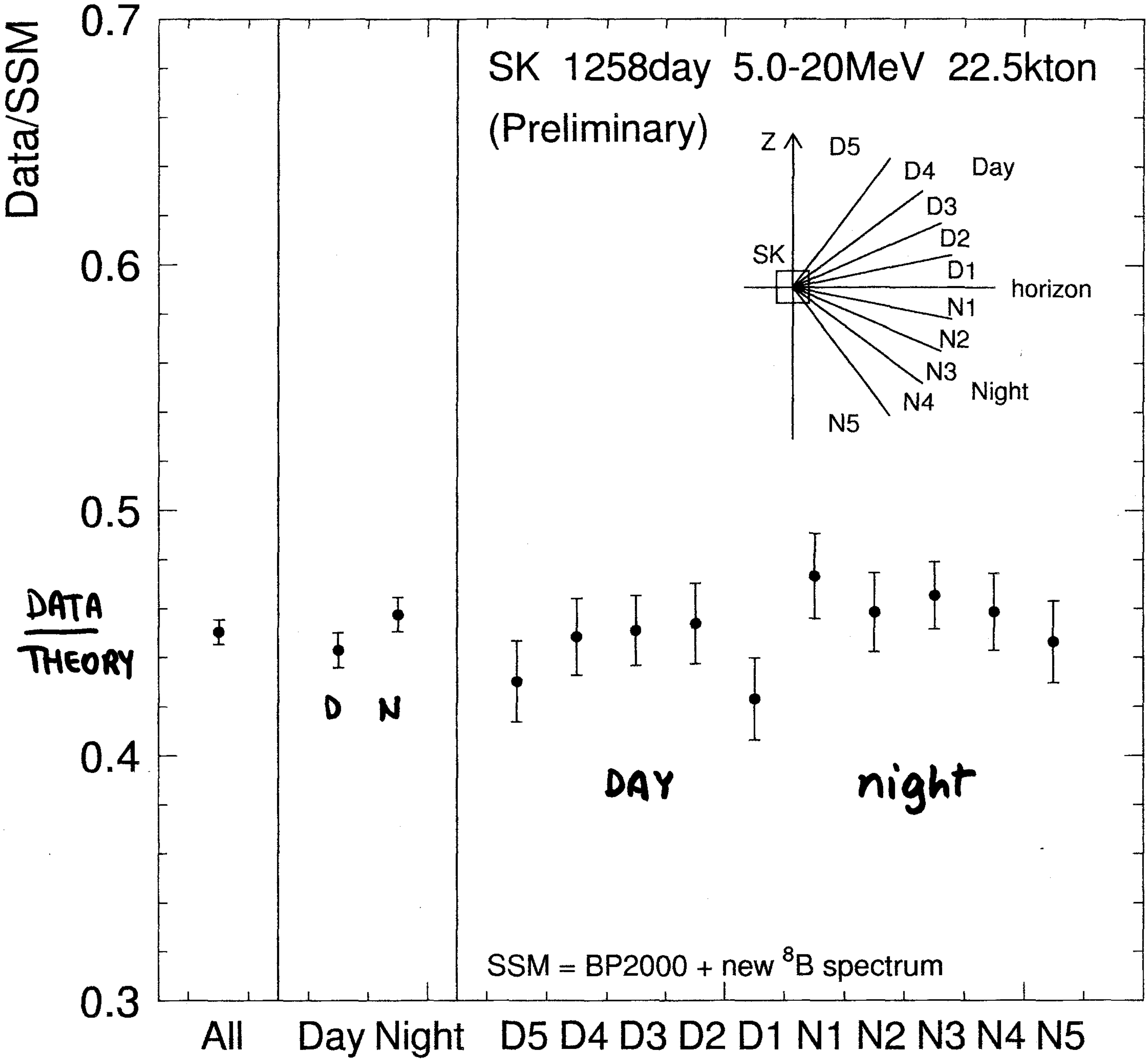
→ NOTHING SEEN

Michael B. Smy, UC Irvine

SK 2001

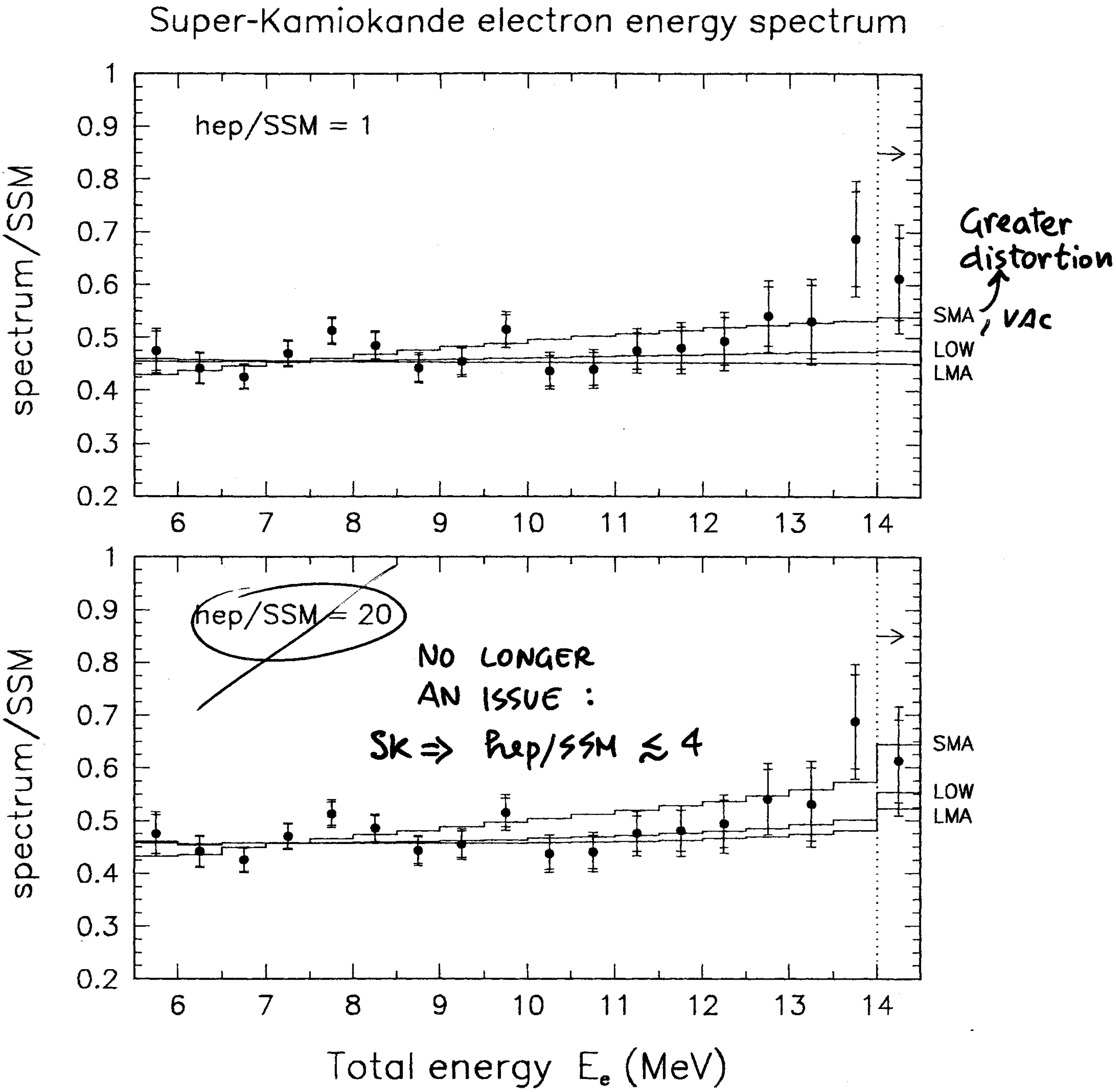
Day/Night

→ EARTH MATTER EFFECTS



Distortion if $\frac{\partial P_{ee}}{\partial N_e^{Earth}} \neq 0$ → NOT SEEN

Michael b. Smy, UC Irvine

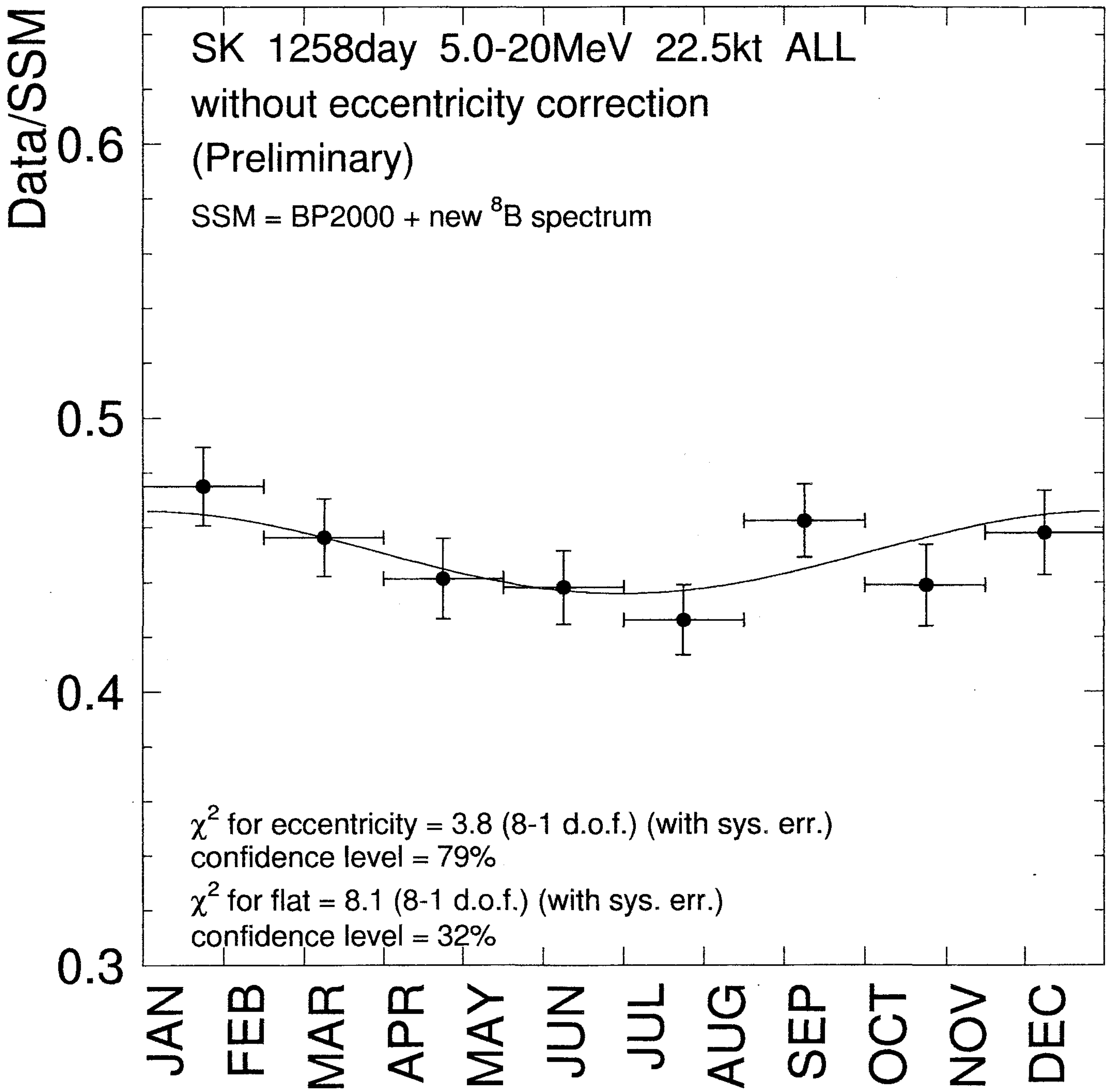


Super-Kamiokande electron energy spectrum
hep/SSM = 1
Greater distortion
SMA , VAc
LOW
LMA
hep/SSM = 20
NO LONGER AN ISSUE :
SK ⇒ hep/SSM ≲ 4
SMA
LOW
LMA
spectrum/SSM
Total energy E_e (MeV)

SK 2001

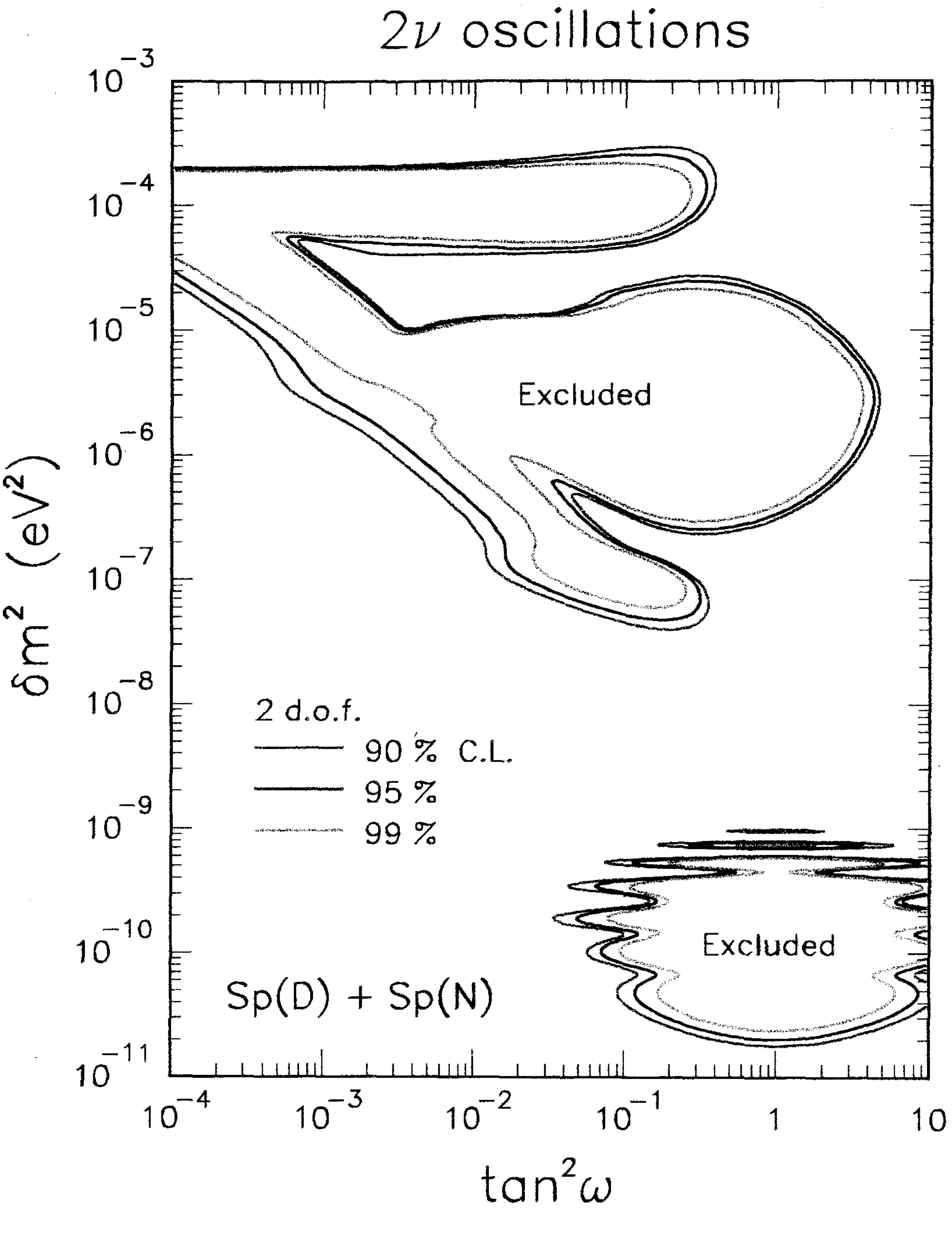
Seas. Variation

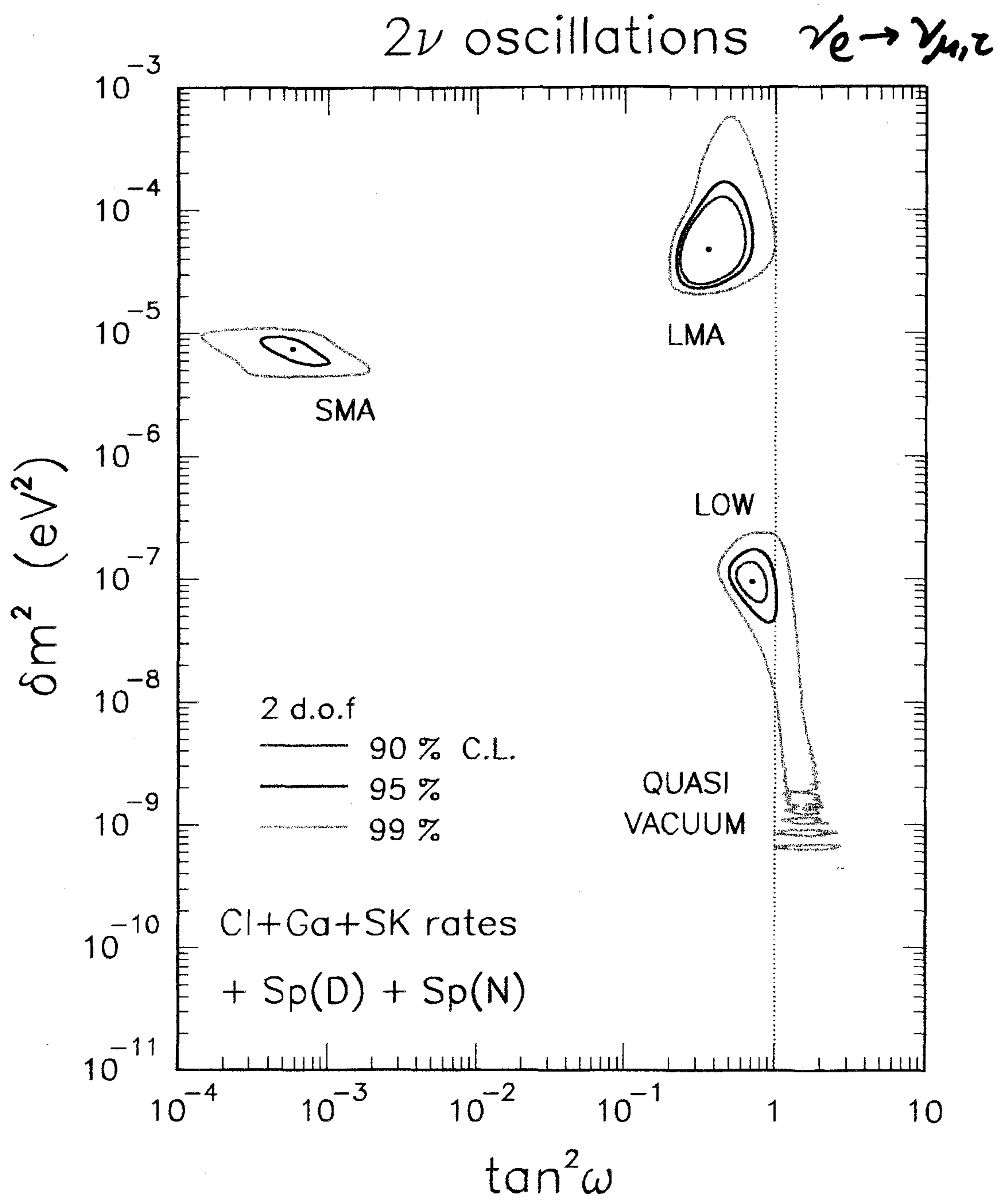
= BASELINE VARIATIONS $L(t) \cong L_0\left(1-\epsilon\cos\frac{2\pi t}{T}\right)$



$1/r^2$ Slightly Favoured over Flat

Distortion if $\frac{\partial P_{ee}}{\partial L} \neq 0$ → NOT SEEN nonobservation of model-independent signals excludes some regions...

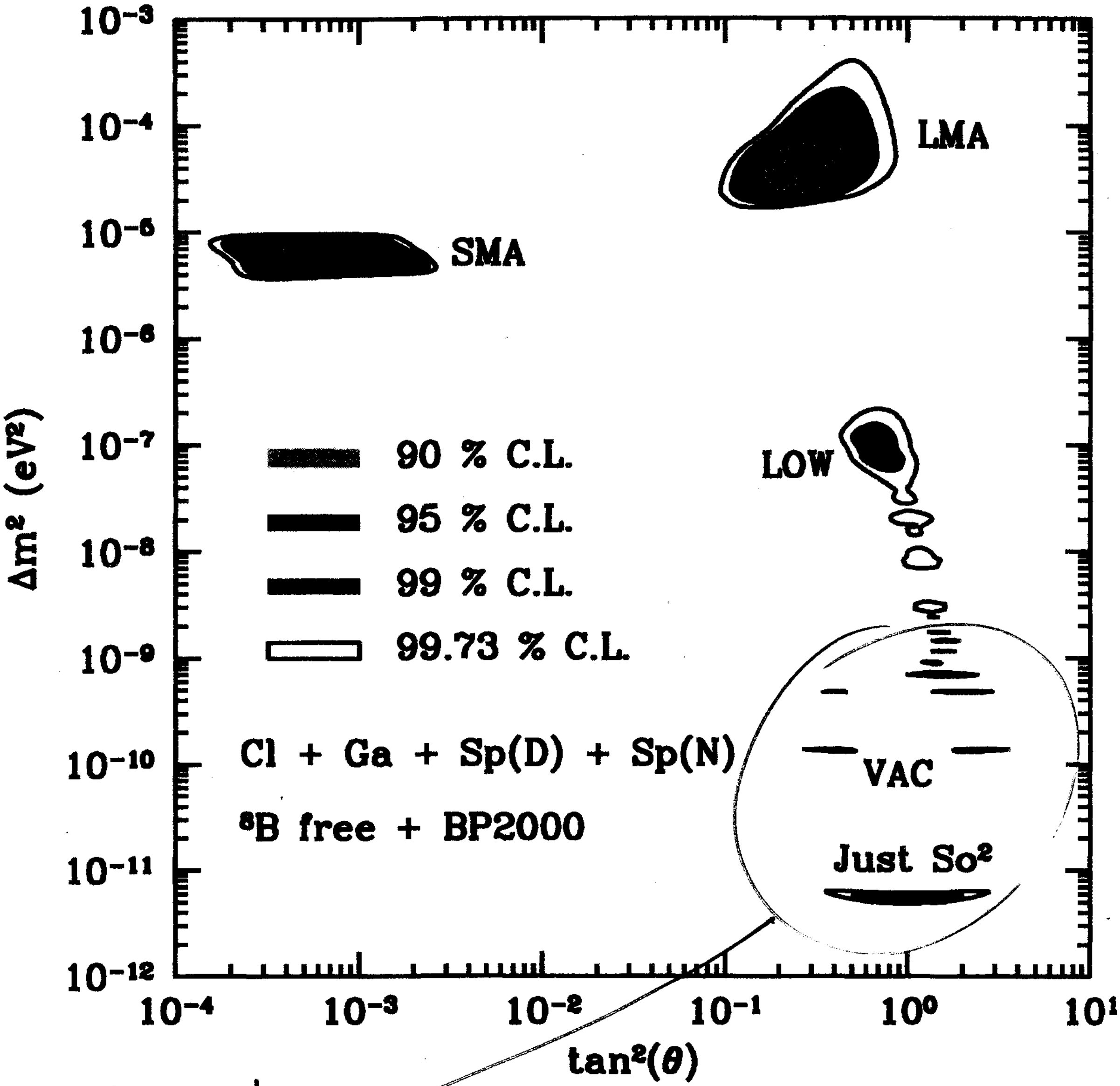




... and changes the likelihood of all solutions

LMA favored → ENORMOUS INTEREST FOR FUTURE ν FACT PROJECTS, WHICH CAN MEASURE (OR BE SENSITIVE) TO Δm^2_{solar} ONLY IF NOT TOO SMALL WITH RESPECT TO Δm^2_{atm}

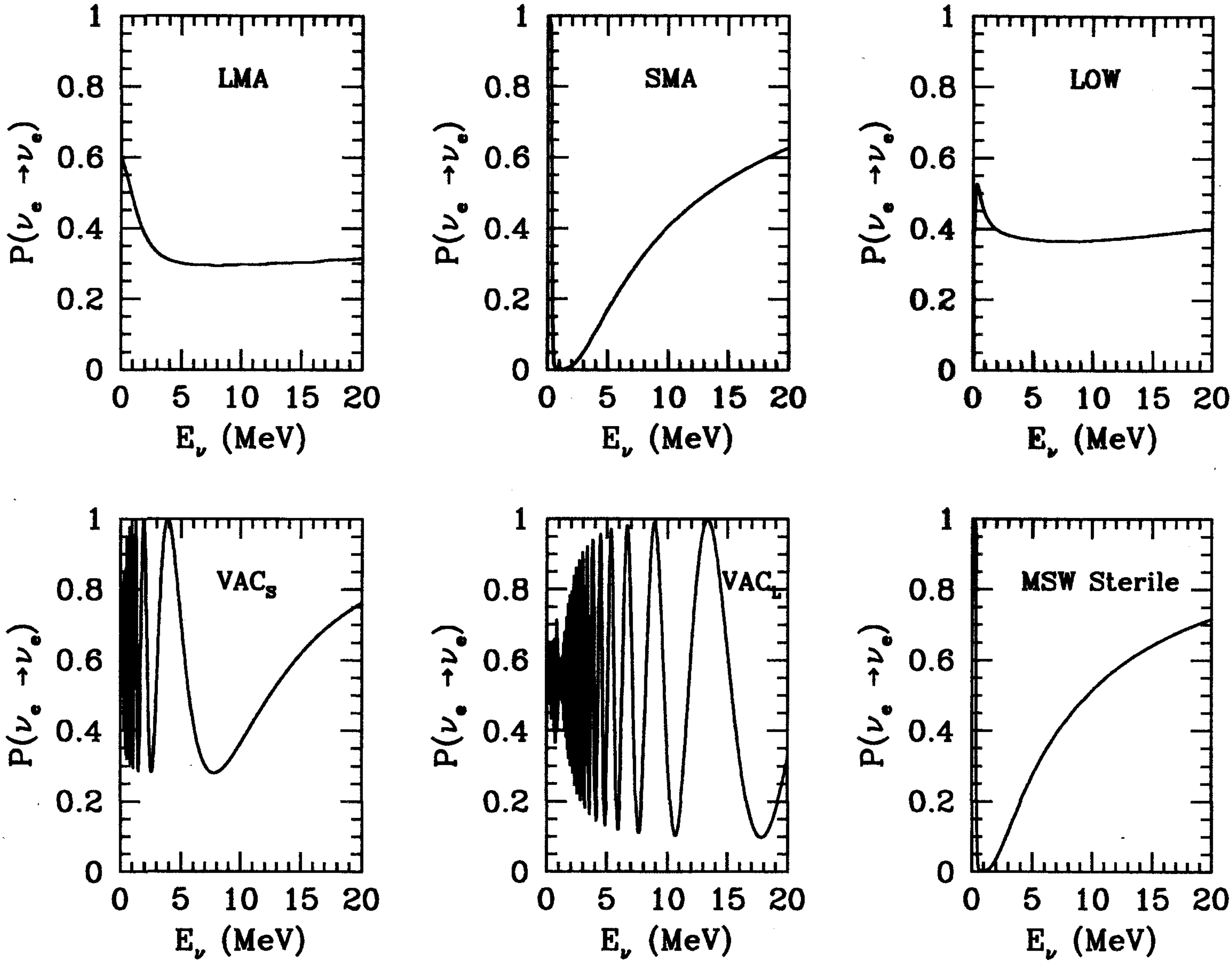
Similar analysis with larger uncertainties (^{8}B flux free) ....



... can get more solutions

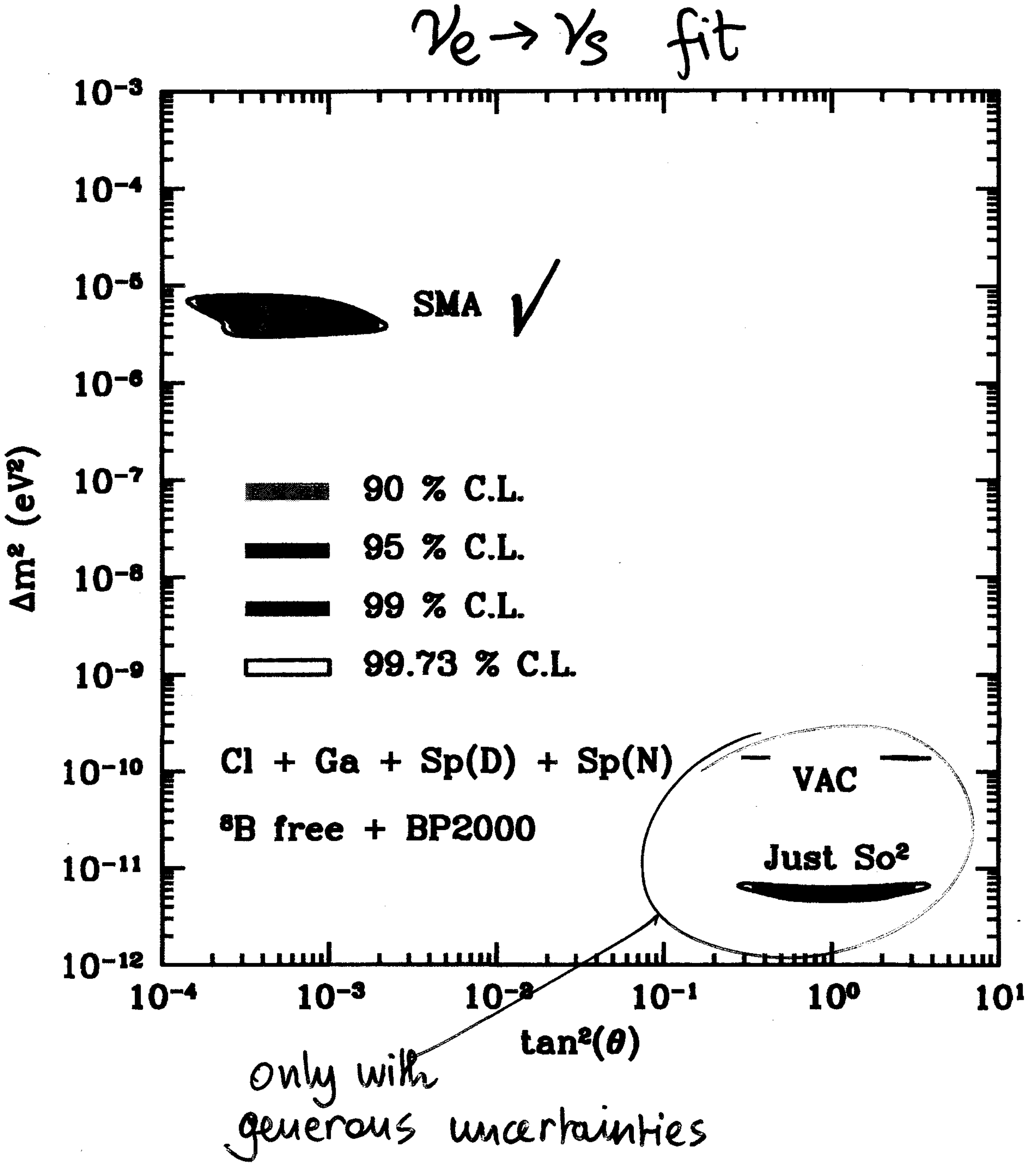
Bahcall
Krastev
Smirnov

As for atm. ν's, oscillation pattern is "hidden" in the data. Here, however, range of possibility is even larger



Bahcall & Krastev

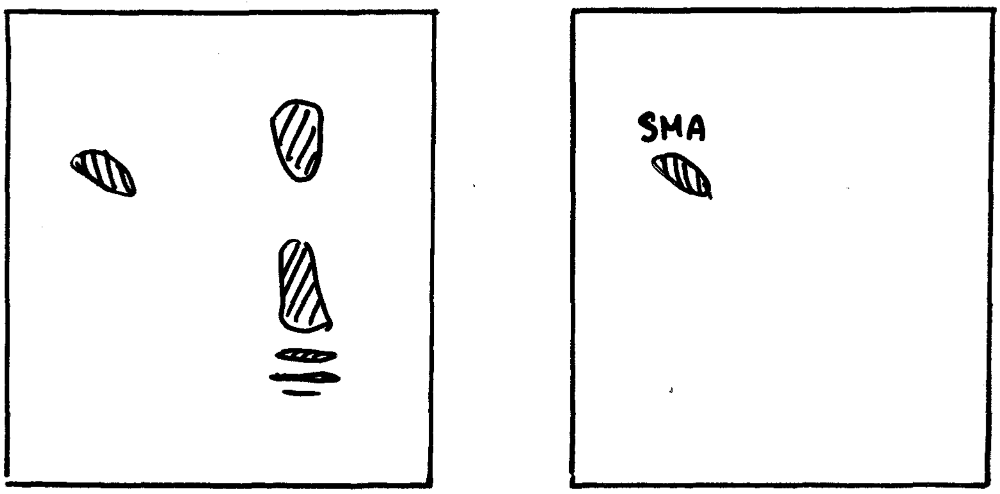
for $\nu_e \to \nu_s$: only SMA survives



$\nu_e \to \nu_s$ fit
SMA
90 % C.L.
95 % C.L.
99 % C.L.
99.73 % C.L.
Cl + Ga + Sp(D) + Sp(N)
^{8}B free + BP2000
VAC
Just So^2
Δm^2 (eV^2)
$\tan^2(\theta)$
only with generous uncertainties

TYPICALLY:

$\nu_e \to \nu_{active}$ $\qquad$ $\nu_e \to \nu_{sterile}$



PREFERRED $\qquad$ POSSIBLE BUT WORSE FIT

- $\nu_e \to \nu_{sterile}$ does not produce NC events in SK $\to$ underestimates SK rate and predicts too strong VAC distortions
- PERTURBING SMA parameters can "adjust" SK without destroying agreement with other data, due to large dP_{ee}/dE_ν in SMA region for E_ν in SK range
- THIS IS NOT POSSIBLE FOR LMA, LOW (rather flat P_{ee} anyway)
- In any case, $\nu_e \to \nu_{sterile}$ fit worse than $\nu_e \to \nu_{active}$

CHOOZ

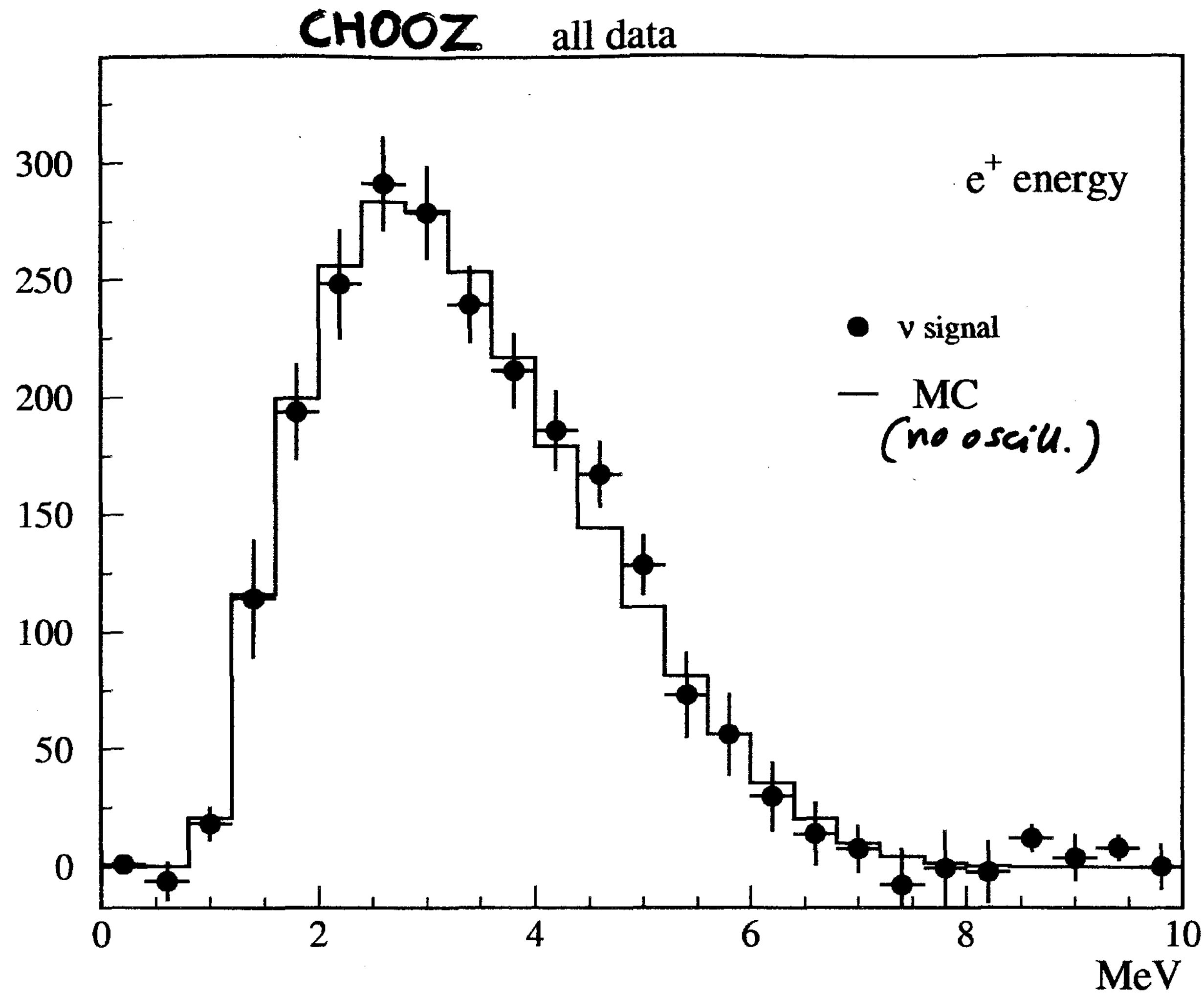
REACTOR EXPERIMENT

$\langle E \rangle \sim$ few MeV

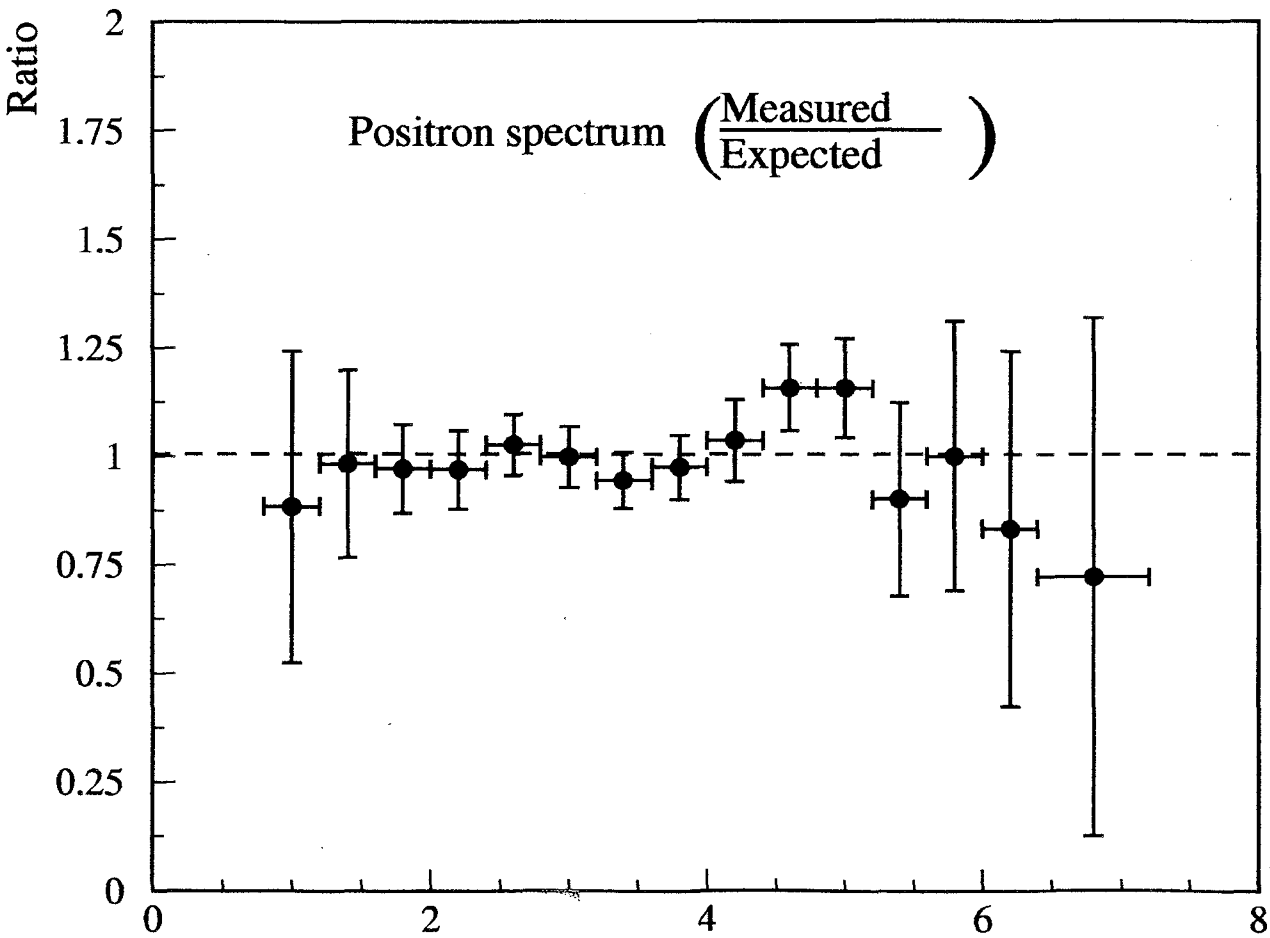
$L \sim 1$ km

CRUCIAL BOUNDS ON $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ DISAPPEARANCE IN Δm^2 range PROBED BY ATM. ν

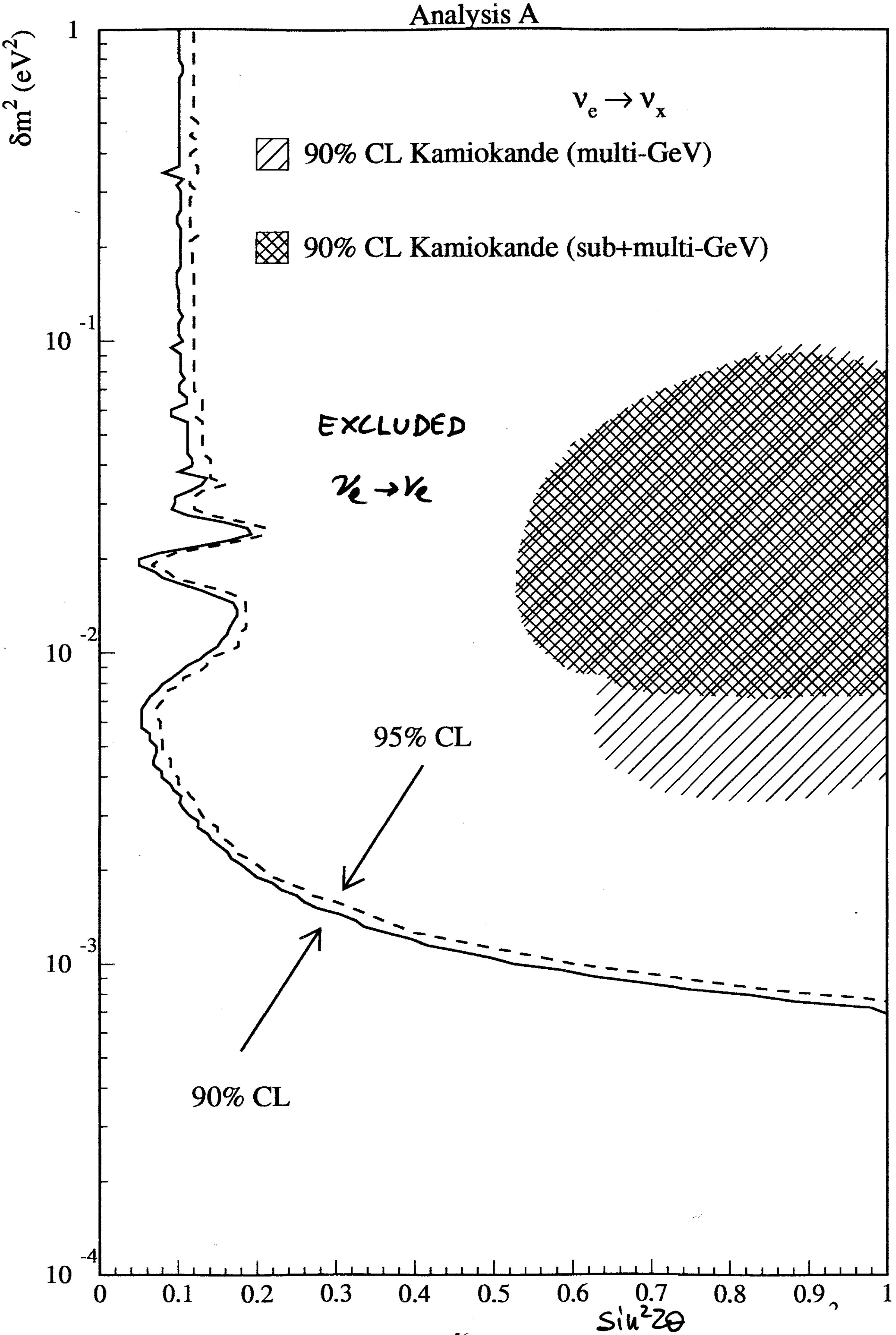
- NO SIGNAL FOUND
- REINFORCES EXCLUSION OF $\nu_\mu \to \nu_e$ as EXPLANATION OF ATM ν DATA
- FORBIDS LARGE $\nu_e \to \nu_e$ TRANSITIONS FOR $\Delta m^2 \gtrsim 0.7 \times 10^{-3}$ eV^2



CHOOZ all data
e+ energy
ν signal
MC
(no oscill.)
MeV



Ratio
Positron spectrum (Measured / Expected)


Analysis A
δm^2 (eV^2)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\nu_e \to \nu_x$
90% CL Kamiokande (multi-GeV)
90% CL Kamiokande (sub+multi-GeV)
EXCLUDED
$\nu_e \to \nu_e$
95% CL
90% CL
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\sin^2 2\theta$

Schematic View of
ν–beam and LSND

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

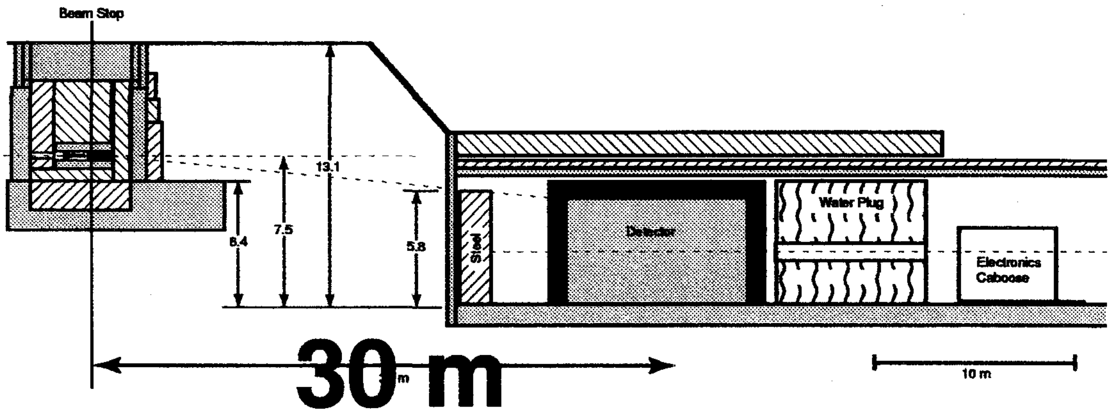


Figure 2: The LSND target/detector geometry.

Detector: 1220 8–inch PMTs
167 tons of Mineral Oil

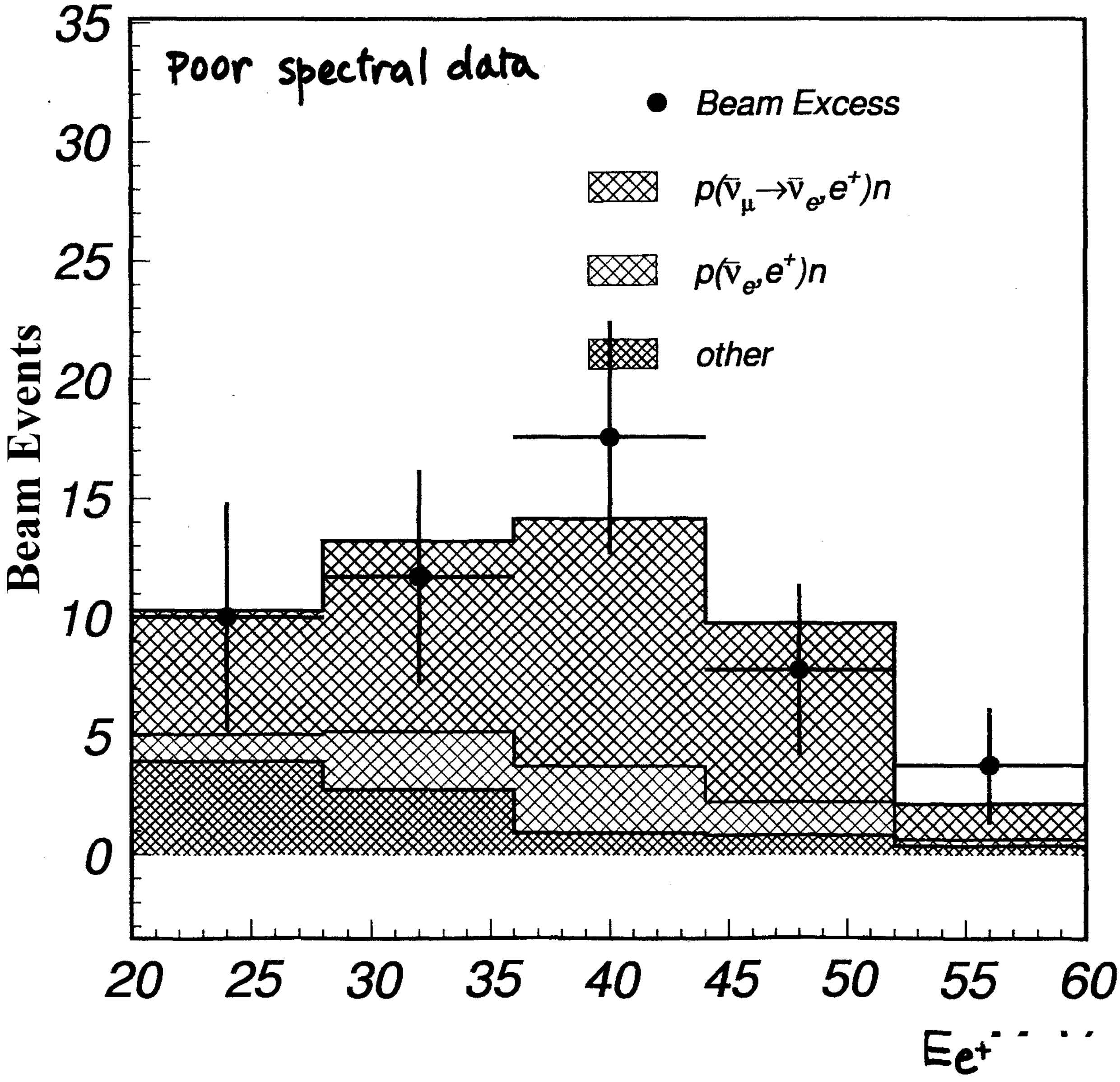
Veto Shield: 292 5–inch PMTs
Active + Passive Shielding

Duty Ratio: ~6%

EXPERIMENTAL EVIDENCE IS CONTROVERSIAL

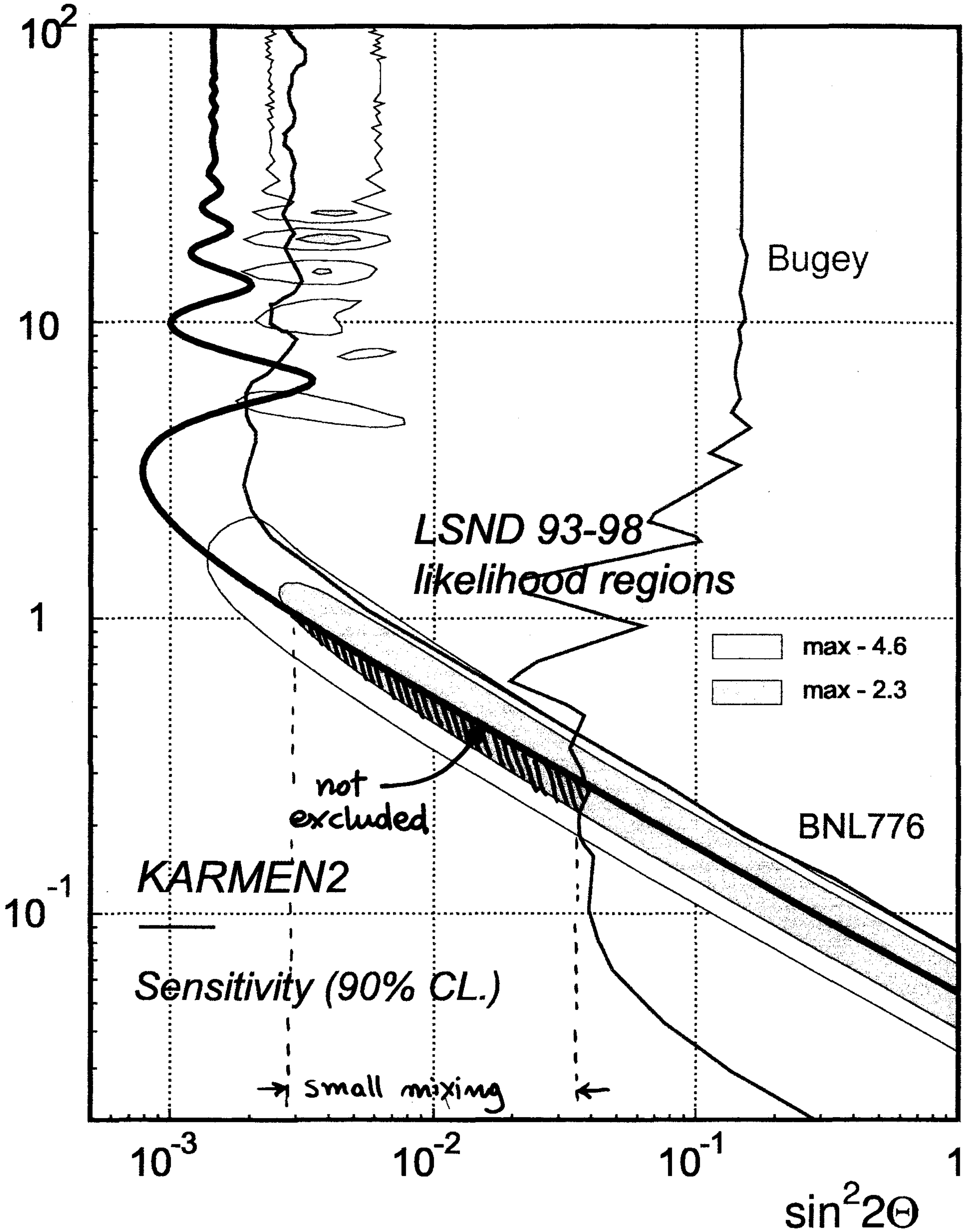
BUT IMPLICATIONS ARE INTERESTING ($m_\nu \sim O(1\,eV)$)

NOTE : $P_{\mu e} \sim$ few ‰ (small)



Expected KARMEN2 Sensitivity

4 years of data taking 2/97-2/01



$\sin^2 2\theta < 1.4 \times 10^{-3}$ (90% CL.)

Sensitivity = 'average' oscillation-limit (MC Basis)

RECAP. (2ν)

• ATMOSPHERIC ν :	$\nu_\mu \to \nu_e$	NO
$\Delta m^2 \sim 3\times10^{-3}\,eV^2$	$\nu_\mu \to \nu_\tau$	OK
	$\nu_\mu \to \nu_s$	strongly disfavored

• SOLAR ν :	$\nu_e \to \nu_{\mu,\tau}$	OK
$\Delta m^2 \lesssim 10^{-3}\,eV^2$	$\nu_e \to \nu_s$	possible but worse fit

---

• CHOOZ : NO ν_e disappearance for $\Delta m^2 \gtrsim 10^{-3}\,eV^2$

• LSND : $\nu_\mu \to \nu_e$ (?)

$\Delta m^2 \sim \mathcal{O}(1\,eV^2)$

NEXT: • COMBINATIONS IN 3ν, 4ν SCHEMES