ARGONNE H INSTITUTE

HEP DIVISION SEMINAR
9-11-2002

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NEUTRINO OSCILLATIONS:

CURRENT STATUS, NEAR FUTURE EXPERIMENTS, AND THE CHALLENGES FOR NEXT-GENERATION LONG-BASELINE EXPERIMENTS

CURRENT STATUS (FLASH REVIEW)

- EVIDENCE (ATM, SOLAR, LSND) FOR NEW PHYSICS
  INTERPRETATION VIA OSCILLATIONS

- NEAR FUTURE
  - WHAT WE HOPE TO LEARN
  - WHAT WILL BE LEFT

  } "MOST BORING SCENARIO"

NEXT-GENERATION
- LBL SET-UP(S)
- CHALLENGES

SOLAR NEUTRINOS

[BIASED TIMELINE]

- FACTOR 2 DISCREPANCY IN RADIOCHEMICAL EXPERIMENT $\xrightarrow{TH}$ MOSTLY IGNORED...

- MSW EFFECT
  KAMIOKANDE, SAGE, GALLEX $\xrightarrow{TH}$ NEUTRINOS HAVE TINY MASSES + TINY MIXING ANGLES (MAYBE...)

- SUPERKAMIOKANDE
  GNO, SNO $\xrightarrow{TH}$ NEUTRINO FLAVOR TRANSITIONS (FOR SURE)
  TINY MASS + LARGE MIXING

ALL DATA PERFECTLY FIT BY 2ν OSCILLATION
WHILE OTHER EXOTIC SOLUTIONS STILL PERSIST...

WHAT IS LEFT

- "SEE" OSCILLATION

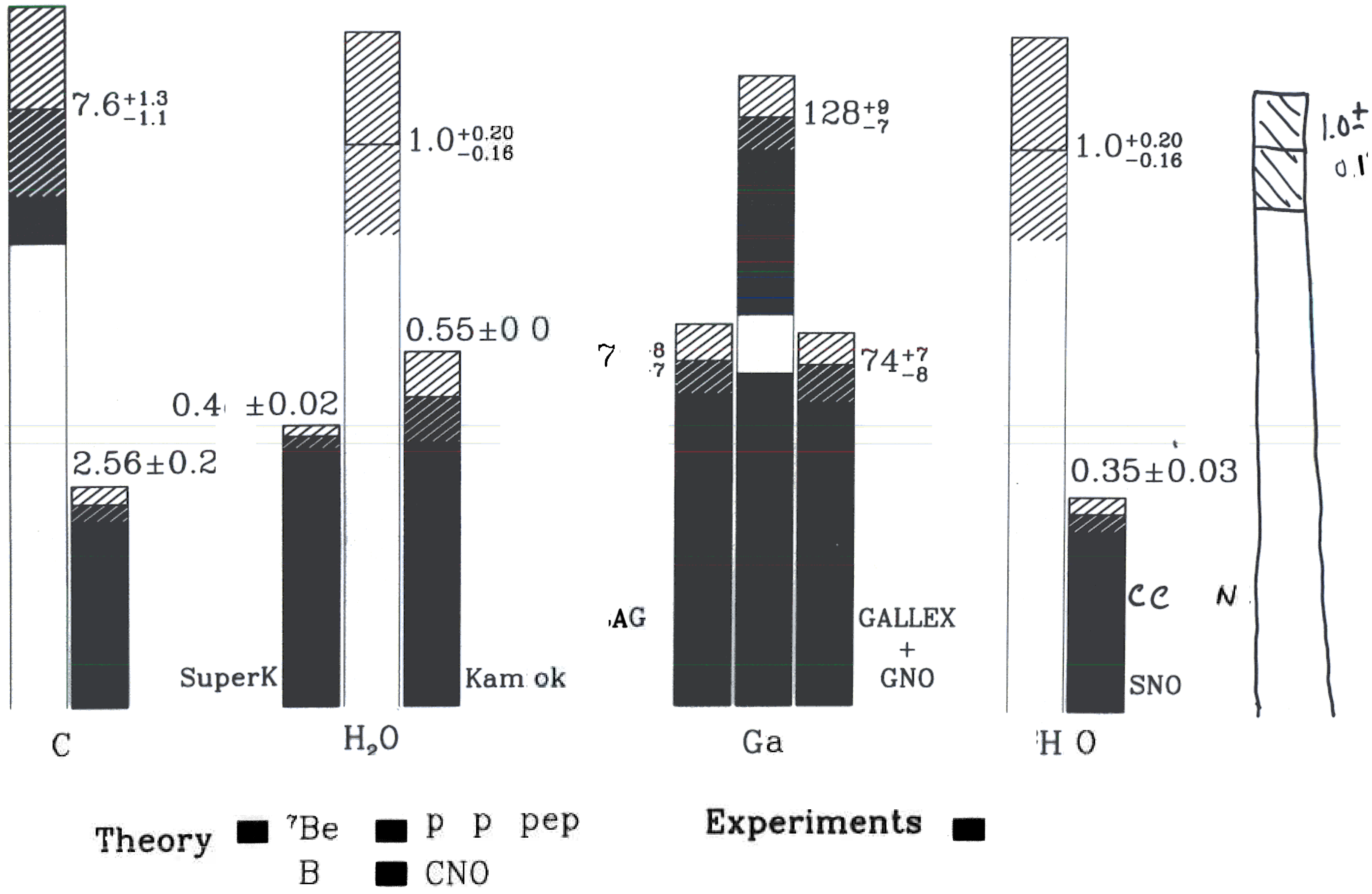
- WHAT IS THE SOLAR SOLUTION?
- WHAT ARE THE SOLAR PARAMETERS?

} BEWARE OF "3σ" REGIONS.

Tota Rate Standard Mode v Exper ment

Bahca P n onneau 2000

ν_e DISAPPEARANCE



SUPERKAMIOKANDE SOLAR NEUTRINO DATA

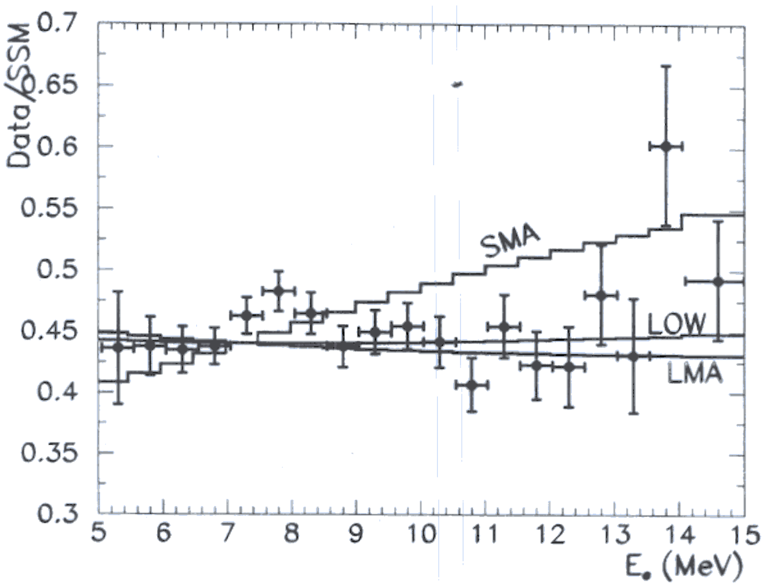


FIG. 11. The electron recoil energy spectrum measured in SK normalized to the SSM prediction, and the expectations for the best fit points for the LMA, SMA and LOW solutions in Tab. IV.

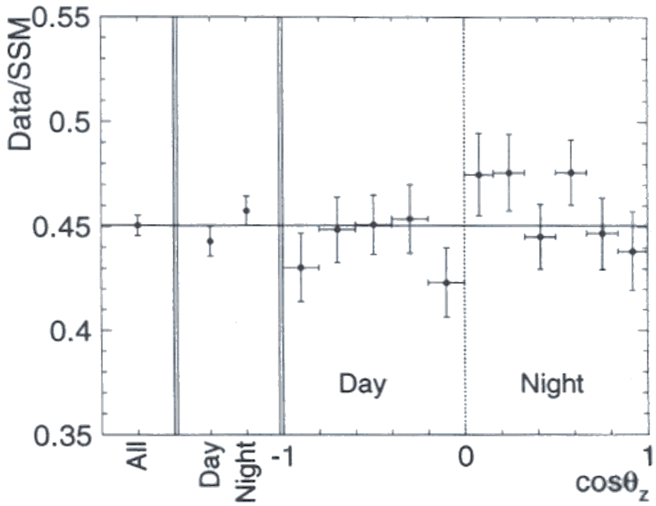
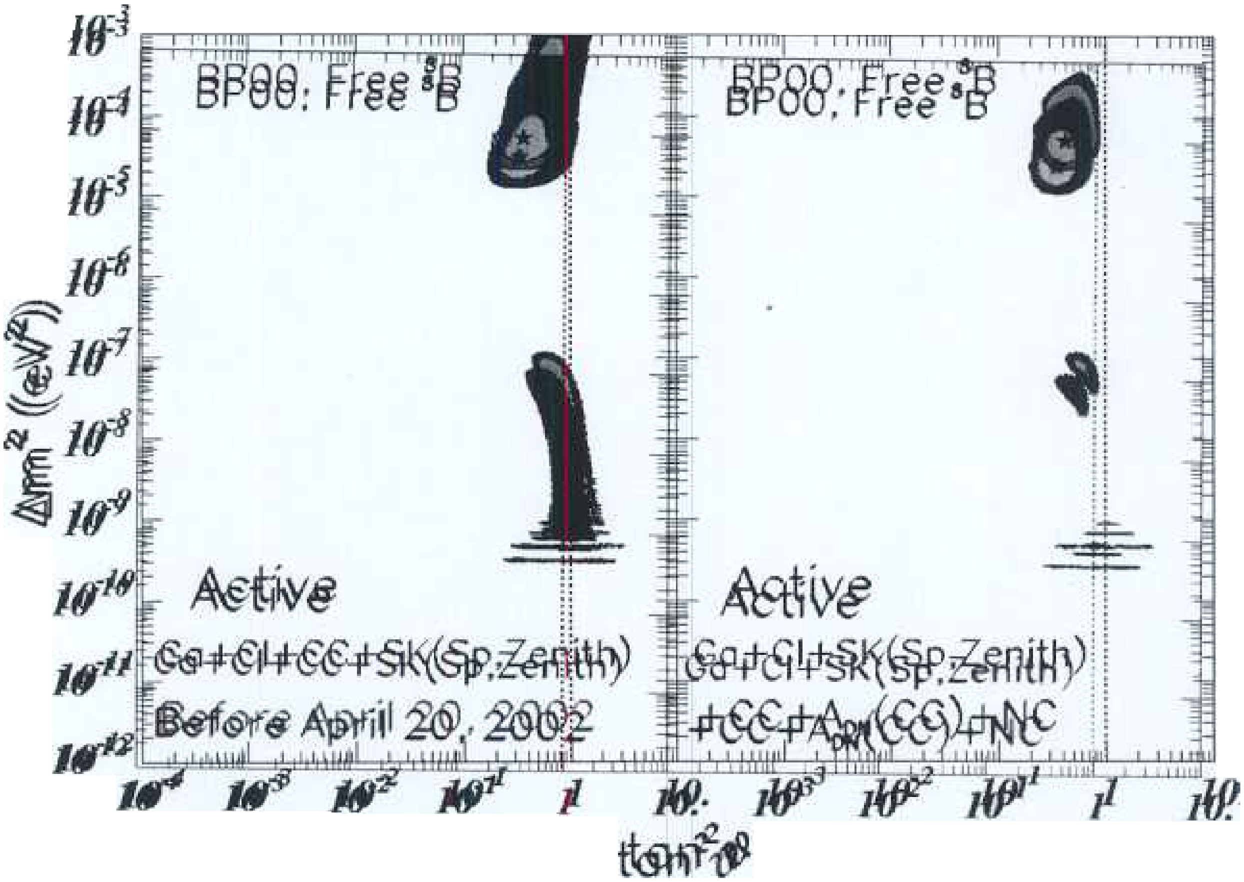


FIG. 12. The zenith angle dependence of the solar neutrino flux (statistical error only). The width of the night-time bins was chosen to separate solar neutrinos that pass through the Earth's dense core ($\cos\theta_z \geq 0.84$) from those that pass through the mantle ($0 < \cos\theta_z < 0.84$). The horizontal line shows the average flux.



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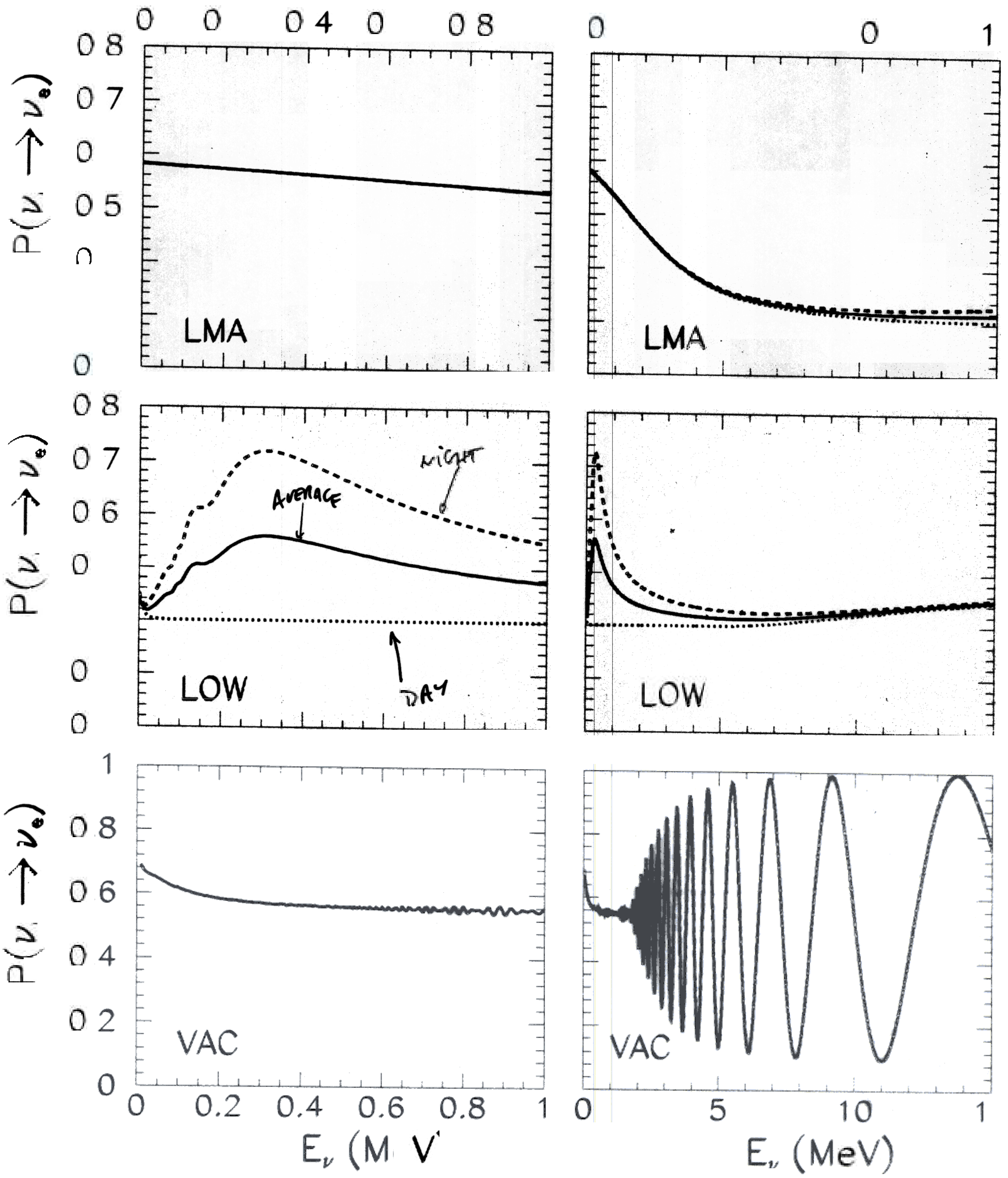

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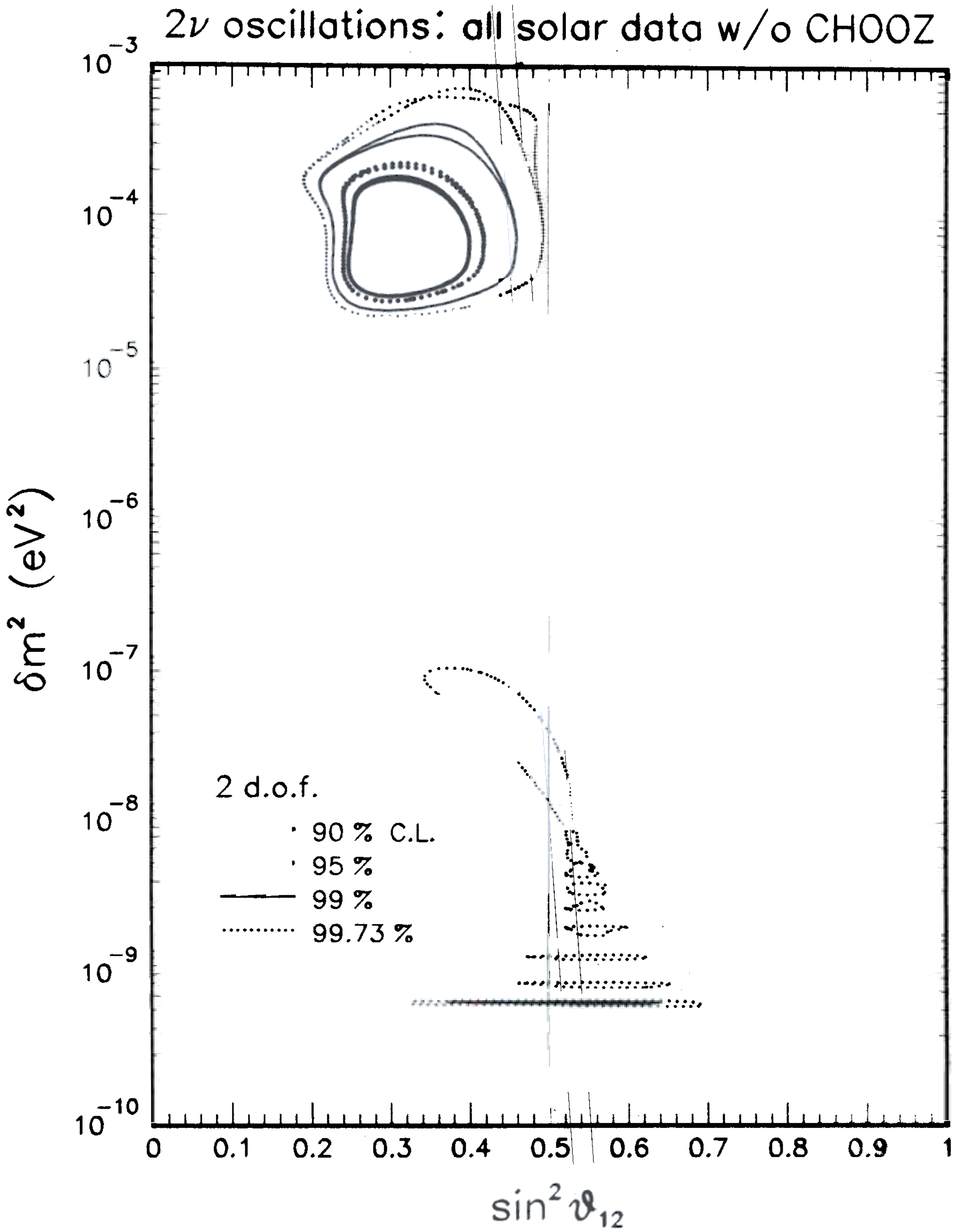


FIG. 1: Two-flavor global analysis of solar neutrino oscillations in the $(\delta m^2, \sin^2\theta_{12})$ parameter space, with and without the additional constraints placed by the CHOOZ reactor experiment. The inclusion of CHOOZ leads to slightly more restrictive upper bounds on δm^2.

ATMOSPHERIC NEUTRINOS

[BIASED HISTORY...

- SUPPRESION OF ν_μ-FLUX AT KAMIOKANDE ET AL $\xrightarrow{TH}$ DISMISSED AS PROBLEM WITH FLUX CALCULATIONS
  "MIXING ANGLES ARE SMALL"

- SUPERKAMIOKANDE 1998 RESULTS $\xrightarrow{TH}$ FIRST UNAMBIGUOS EVIDENCE FOR NEW PHYSICS.
  MIXING ANGLE IS $\pi/4$!

- K2K: OSCILLATIONS OF TERRESTRIAL ν_μ's $\xrightarrow{TH}$ AGREES WITH EXPECTATIONS FROM ATM DATA.

ALL DATA PERFECTLY FIT BY 2ν ($\nu_\mu \leftrightarrow \nu_2$) OSCILLATIONS

EXOTIC SOLUTIONS SLOWLY DYING AWAY...

WHAT IS LEFT

- "SEE" OSCILLATIONS
- MEASURE PARAMETERS

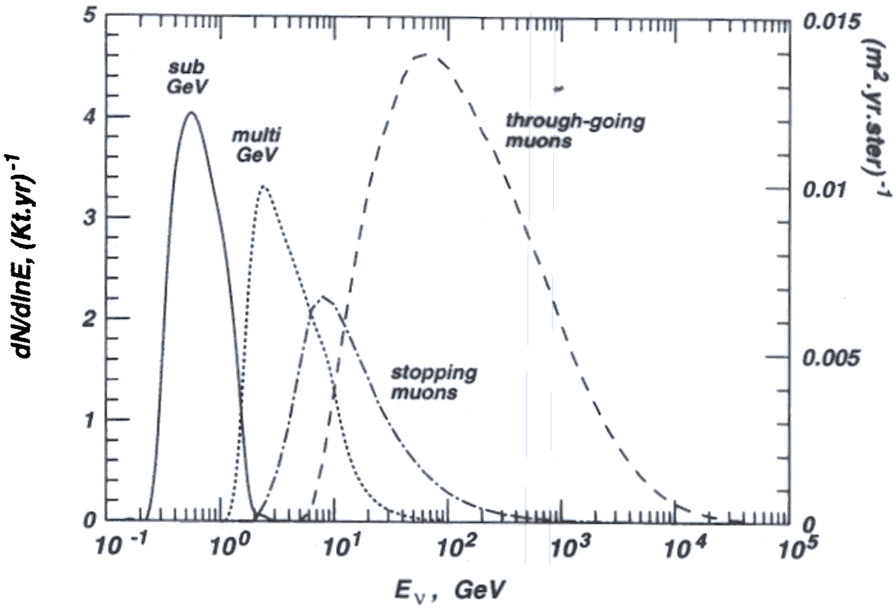


FIG. 19. Event rates as a function of neutrino energy for fully contained events, stopping muons, and through-going muons at SuperKamiokande.

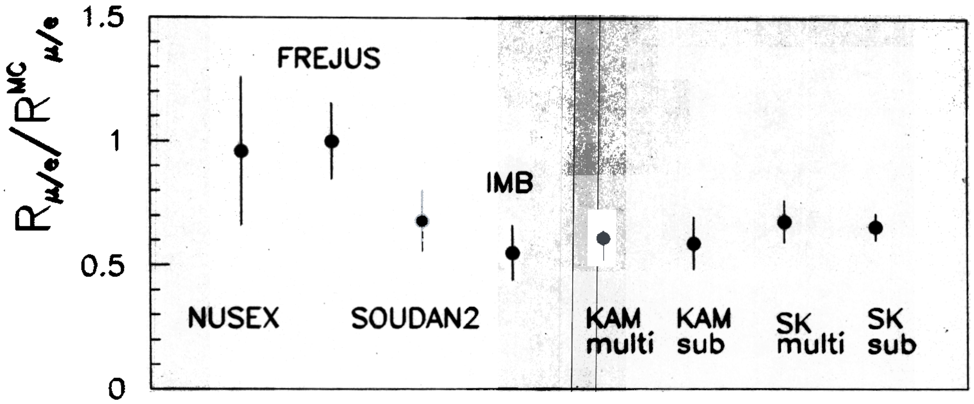


FIG. 20. The double ratio of ν_μ to ν_e events, data divided by theoretical predictions, for various underground atmospheric neutrino detectors.

SUPERKAMIOKANDE ATMOSPHERIC NEUTRINO

$\nu_\mu, \bar{\nu}_\mu$ DISAPPEARANCE

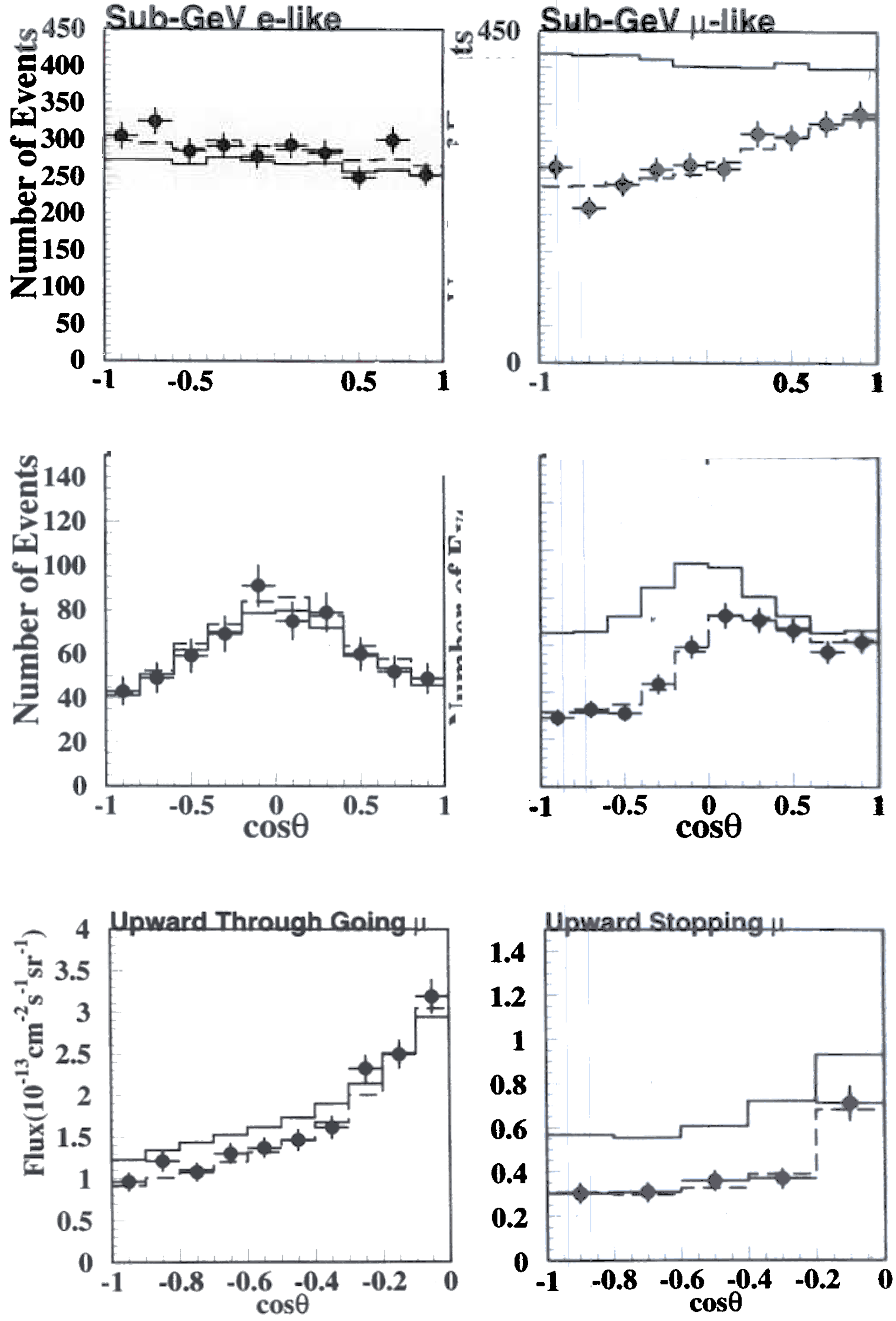


FIG. 21. Zenith angle distribution of SuperKamiokande 1289 days data samples. Dots, solid line and dashed line correspond to data, MC with no oscillation and MC with best fit oscillation parameters, respectively.

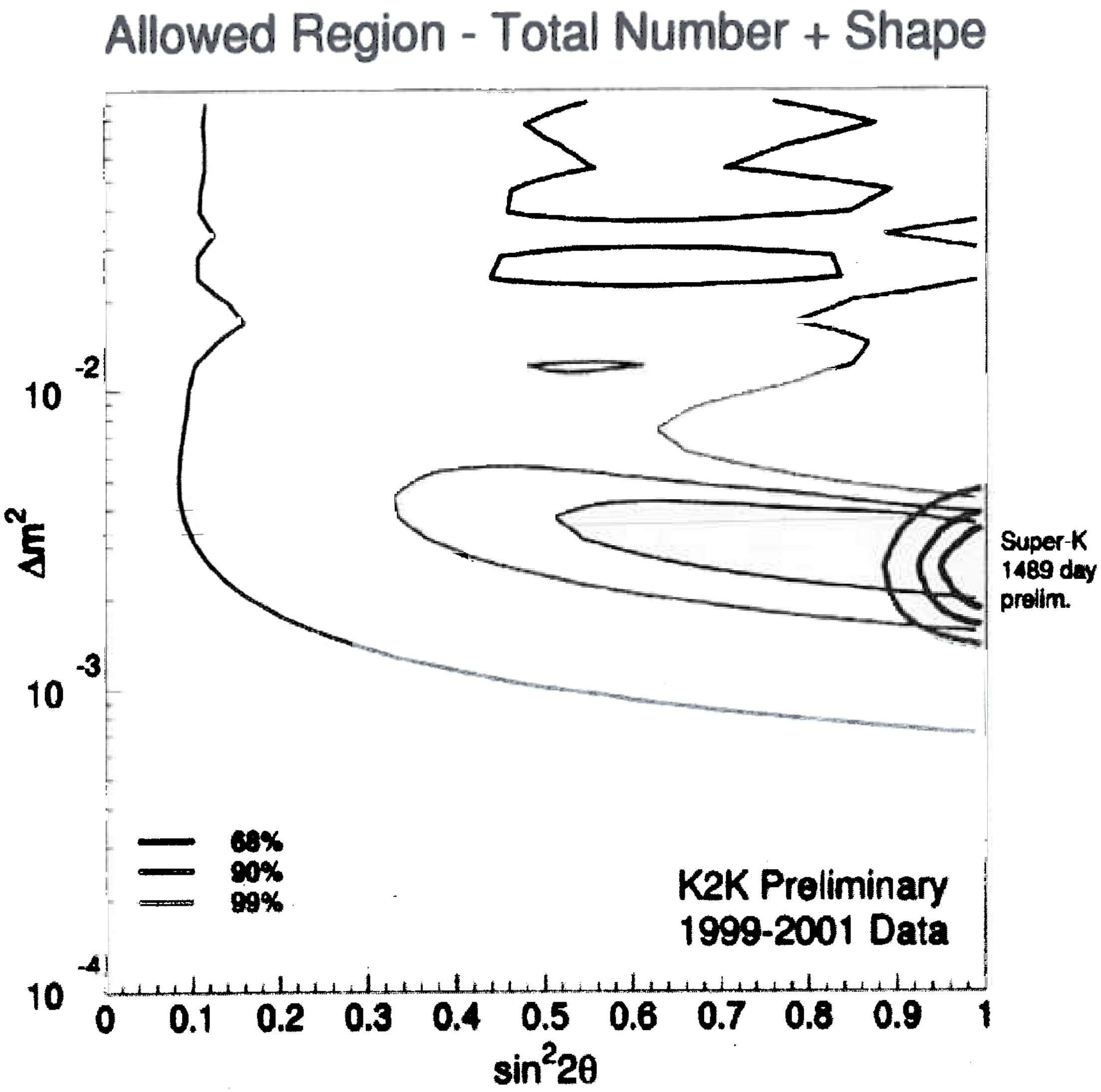
K2K TALK
AT
NEUTRINO 2002

Null Oscillation Probability

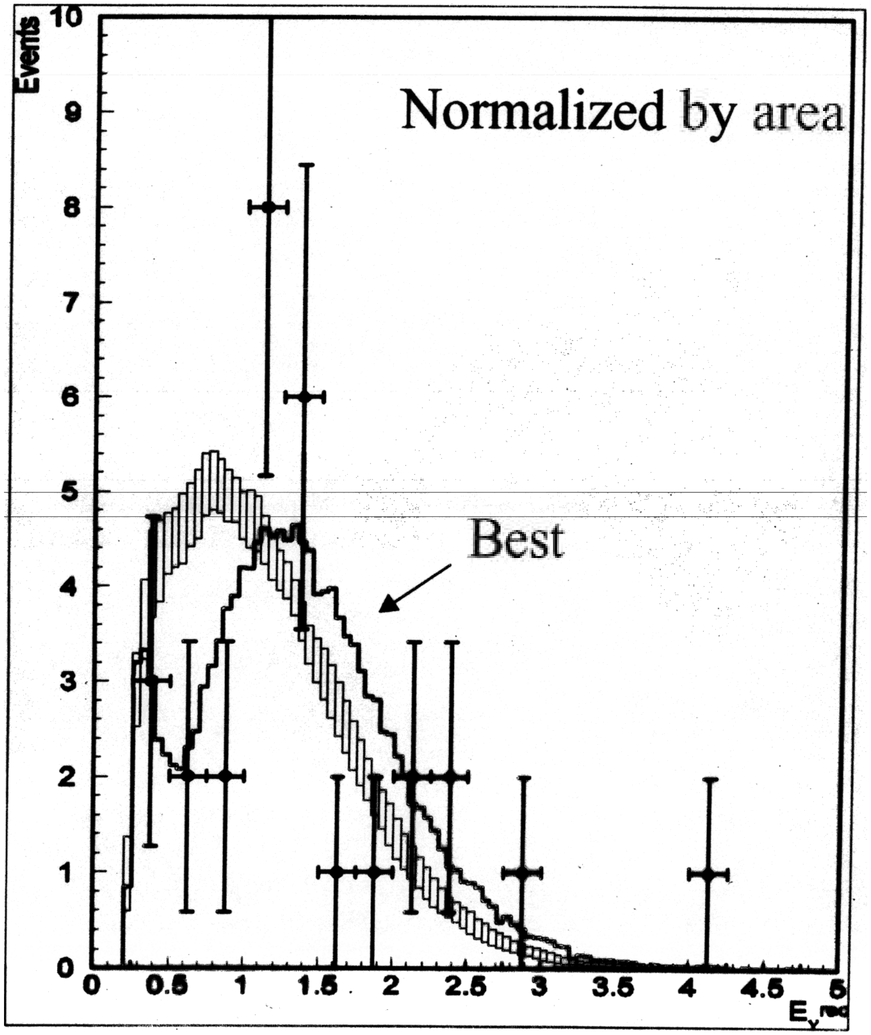
Null Oscillation Probability	method-1	method-2
N_{SK}only	1.3%	0.7%
Shape only	15.7%	14.3%
N_{SK}+Shape	0.7%	0.4%

Best fit ($\sin^2 2\theta$, Δm^2)		
Shape only	(1.0, $3.0\times10^{-3}eV^2$)	(1.0, $3.2\times10^{-3}eV^2$)
(Allowing unphys.)	(1.09, $3.0\times10^{-3}eV^2$)	(1.05, $3.2\times10^{-3}eV^2$)
N_{SK} +Shape	(1.0, $2.8\times10^{-3}eV^2$)	(1.0, $2.7\times10^{-3}eV^2$)
(Allowing unphys.)	(1.03, $2.8\times10^{-3}eV^2$)	(1.05, $2.7\times10^{-3}eV^2$)

Comparison with SK atm ν observation



Is best fit point also for 1Rμ shape & Nsk ?



Best fi point $\sin^2 2\theta$ Δm

me hod

KS test prob shape)= 79%

N_{SK} prediction 54 (ob 56)

method 2	KS-te t
N_{SK}	82%
shape	93%
N_{SK}+shape	50%

THE LSND ANOMALY

[BIASED HISTORY...]

- EVIDENCE FOR $\nu_\mu \to \nu_e$ TRANSITIONS ($\sim 3\sigma$)
  EVENTS AT "THE BOTTOM"

- EVIDENCE FOR $\bar{\nu}_\mu \to \bar{\nu}_e$ TRANSITIONS ($\sim 3\sigma$)
  NO OBVIOUS "PROBLEM" $\nu_\mu \to \nu_e$ EVIDENCE
  WEAKER (CONSISTENT WITH $\emptyset$ AND $\bar{\nu}_\mu \to \bar{\nu}_e$)

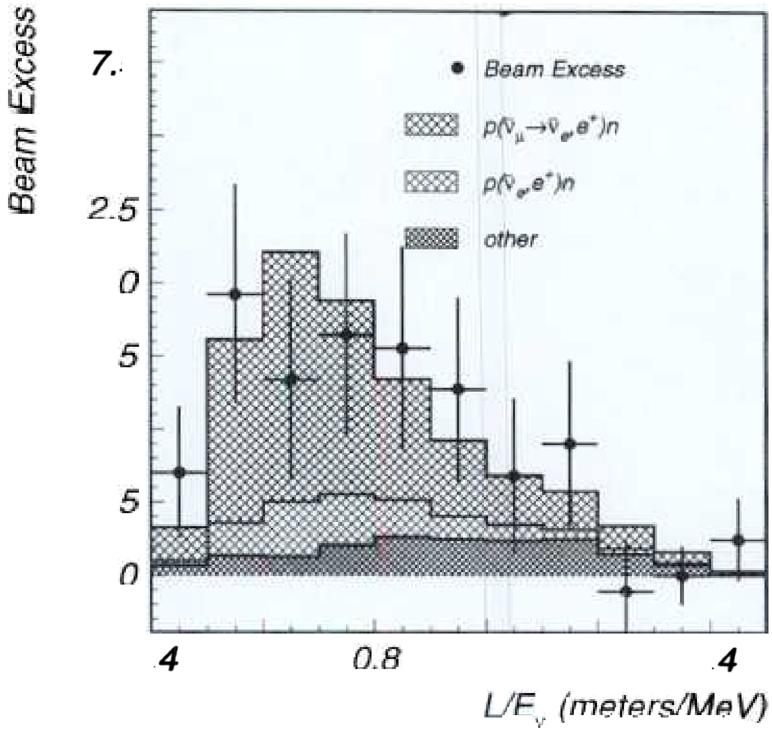
PERFECTLY FIT BY 2ν ($\nu_\mu \leftrightarrow \nu_e$) OSCILLATIONS)

TH → MOST PEOPLE DON'T BELIEVE LSND "FOR REAL" LOTS OF ROOM FOR SPECULATION, NO CONSENSUS.

WHAT IS LEFT TO DO?

MINIBOONE

RESULTS IN 2 YEARS!



G E_ν lis ibu en R_γ an 20 E 60 Me' he istance velled by the no mete and E he energy Me' The agree well he pectation neu backgro nd an llations at low Δ

LSND DATA

$\bar{\nu}_\mu \to \bar{\nu}_e$ TRANSITION

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

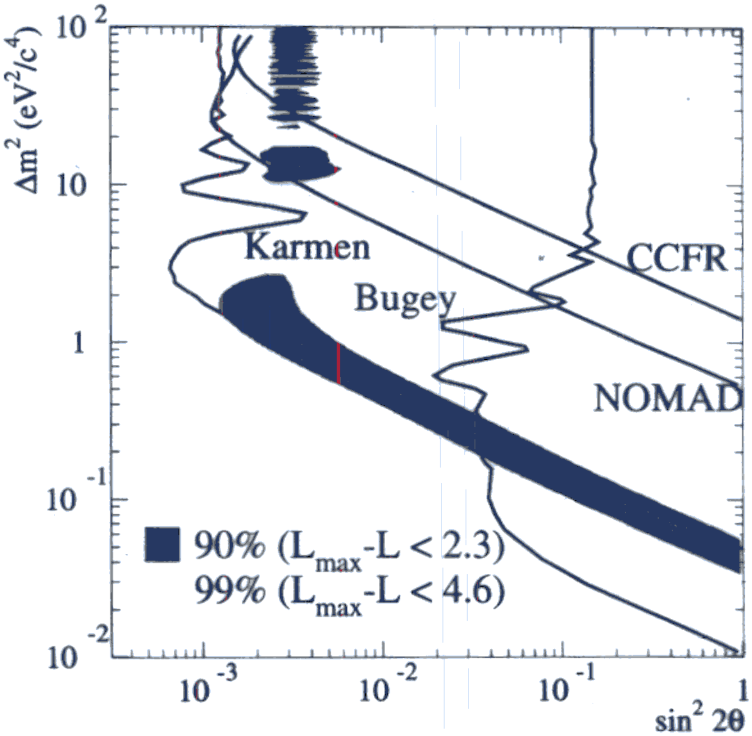


FIG. 23: A ($\sin^2 2\theta, \Delta m^2$) oscillation parameter fit for the entire data sample, $20 < E_e < 200$ MeV. The fit includes primary $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and secondary $\nu_\mu \rightarrow \nu_e$ oscillations, as well as all known neutrino backgrounds. The inner and outer regions correspond to 90% and 99% CL allowed regions, while the curves are 90% CL limits from the Bugey reactor experiment, the CCFR experiment at Fermilab, the NOMAD experiment at CERN, and the KARMEN experiment at ISIS.

LSND Coll.

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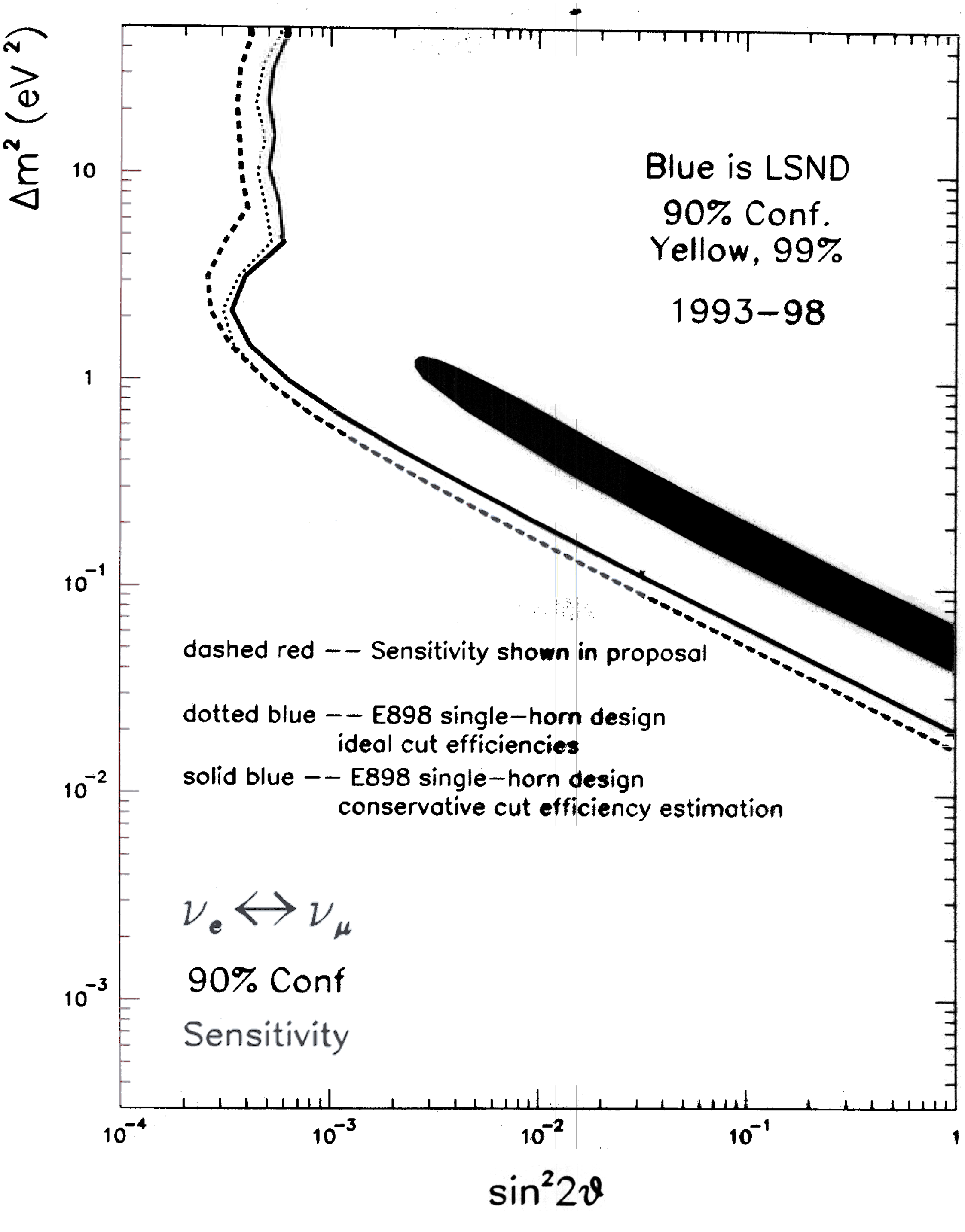
SENSITIVITY OF THE MINI BOONE EXPERIMENT



START OF DATA TAKING → END OF JUNE 2002

- ALL PROBLEMS ARE INDIVIDUALLY SOLVED BY <u>2</u> FLAVOR OSCILLATIONS:

SOLAR	$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$	$\Delta m^2 \lesssim 10^{-4} eV^2$ LARGE MIXING	★★★
ATMOSPHERIC	$\nu_\mu \leftrightarrow \nu_\tau$ $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_\tau$	$\Delta m^2 \sim 10^{-3} eV^2$ LARGE MIXING	★★★
LSND + KARMEN + REACTOR	$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$	$\Delta m^2 \gtrsim 10^{-1} eV^2$	★?

- ANY 2 PROBLEMS CAN BE SIMULTANEOUSLY SOLVED BY <u>3</u> FLAVOR OSCILLATIONS

<u>HOWEVER</u>, THE 3 PROBLEMS <u>CANNOT</u> BY ADDRESSED SIMULTANEOUSLY !!

[BY 3 FLAVOR OSCILLATIONS ONLY...]

THE MOST CONSERVATIVE SCENARIO:

3-FLAVOR NEUTRINO OSCILLATIONS

- IGNORE LSND ANOMALY
- FIT SOLAR + ATMOSPHERIC + REACTOR DATA TO OBTAIN PARAMETERS
  ↳ [CHOOZ PLOT →]

OSCILLATIONS

$\nu_\alpha = U_{\alpha i} \nu_i$

$\alpha = e, \mu, \tau$ → WEAK EIGENSTATES

$i = 1, 2, 3$ → MASS EIGENSTATES

MASSES m_i^2

$$i \frac{d}{dx} \nu_\alpha = H_{\alpha\beta} \nu_\beta$$

$$H = U \begin{bmatrix} 0 & & \\ & \frac{\Delta m^2_{12}}{2E} & \\ & & \frac{\Delta m^2_{13}}{2E} \end{bmatrix} U^\dagger + \begin{bmatrix} \sqrt{2} G_F N_e(x) & & \\ & 0 & \\ & & 0 \end{bmatrix} + K \mathbb{1}$$

PARAMETERIZING 3ν OSCILLATIONS

DEFINE MASS EIGENSTATES

$$0 < \Delta m^2_{12} < |\Delta m^2_{13}|, |\Delta m^2_{23}|$$

WITHIN THIS DEFINITION + GIVEN THE CURRENT DATA

- $tg^2\theta_{SOL} = tg^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}$ • $\Delta m^2_{SOL} = \Delta m^2_{12}$

- $tg^2\theta_{ATM} = tg^2\theta_{23} = \frac{|U_{\mu 3}|^2}{|U_{23}|^2}$ • $|\Delta m^2_{13}| \sim |\Delta m^2_{23}| = \Delta m^2_{ATM}$

- $sen^2\theta_{13} = |U_{e3}|^2$ → CONSTRAINED BY CHOOZ

- CP-ODD PHASE

$$\left[J = Im \left[U^*_{e3} U_{\mu 3} U_{e2} U^*_{\mu 2} \right] = \frac{1}{8} \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \times \right.$$

$$\times \underline{sen\,\delta}$$

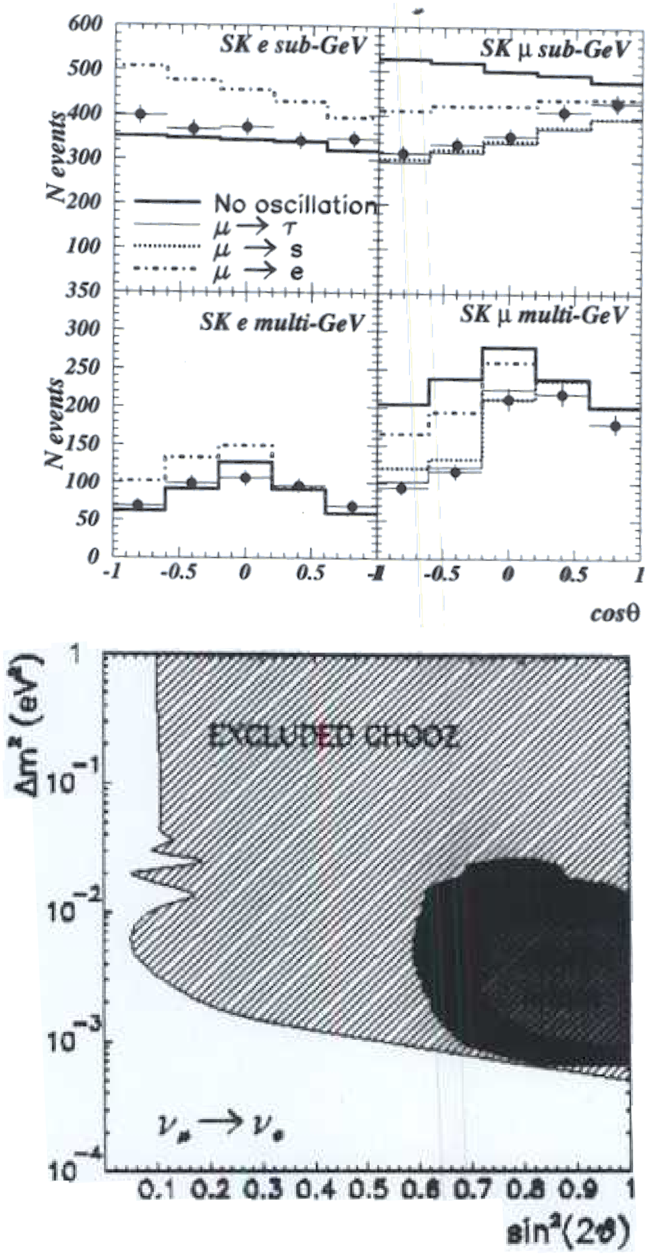


FIG. 28. The status of the $\nu_\mu \to \nu_e$ oscillation solution to the atmospheric neutrino anomaly.

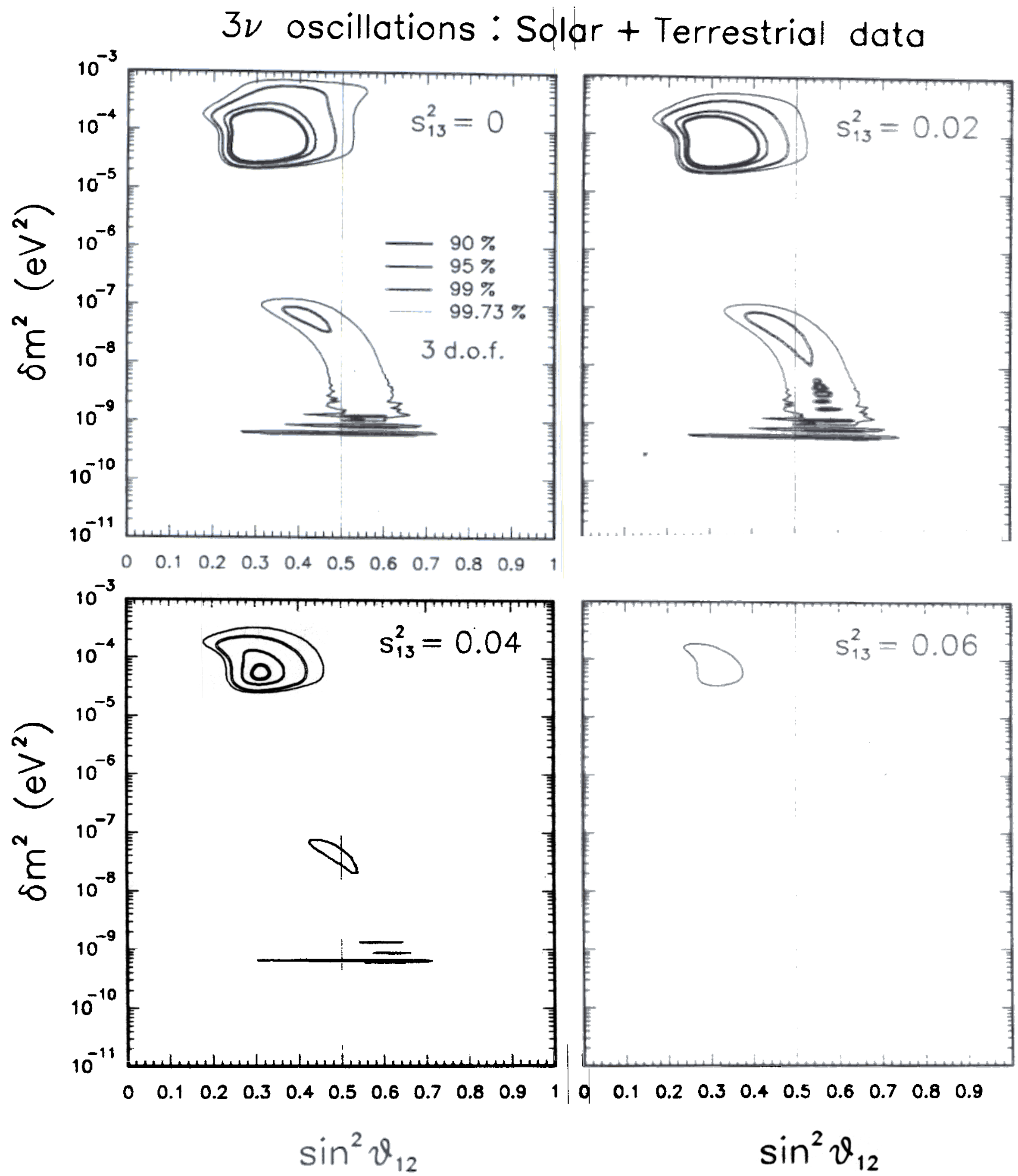


FIG. 3: As in Fig. 2, but including the constraints from terrestrial neutrino oscillation searches at CHOOZ, SK, and K2K.

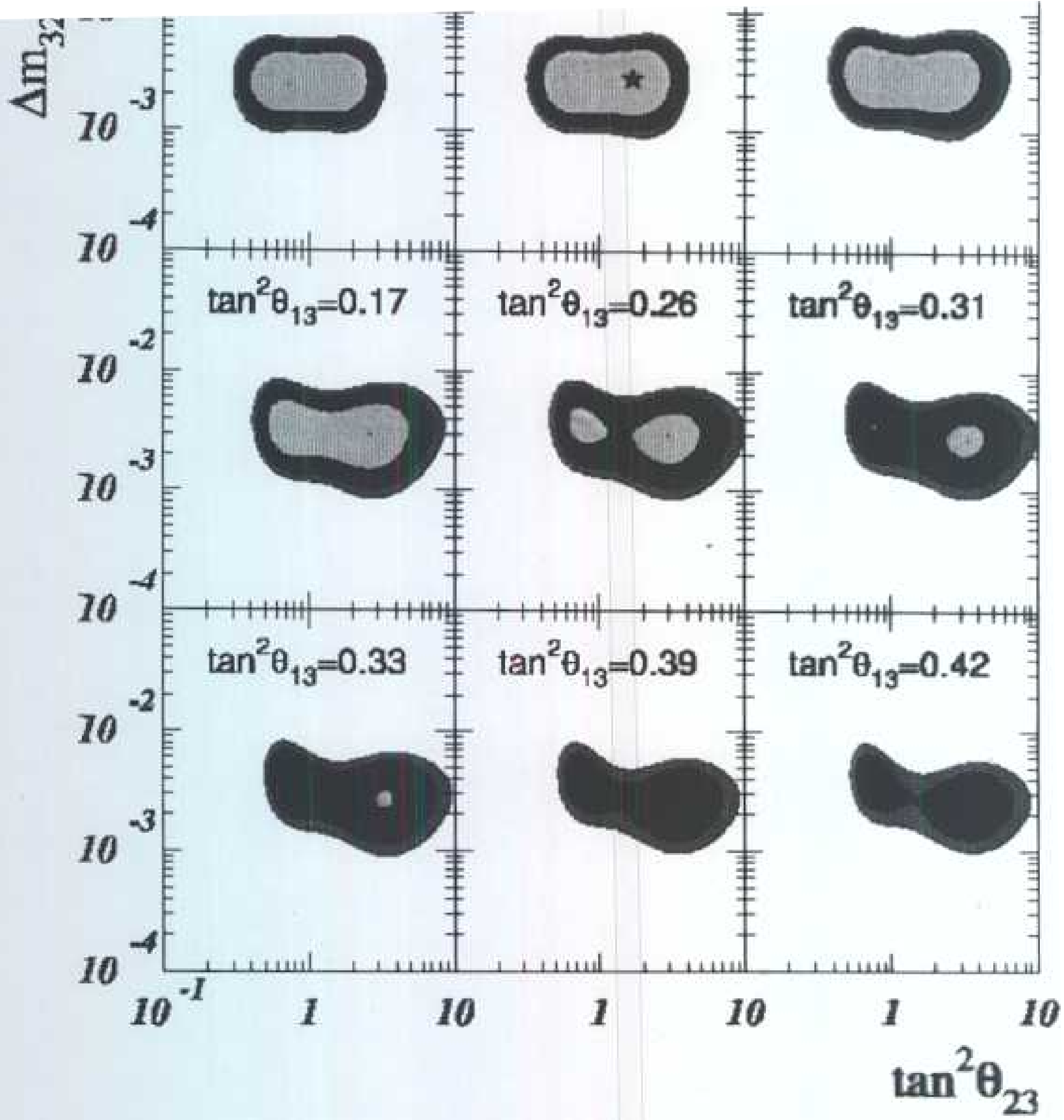


FIG. 38. Allowed regions (at 90, 95, 99, and 99.7% CL) in the $(\Delta m^2_{32}, \tan^2\theta_{23})$ plane from th global analysis of the atmospheric neutrino data in the framework of three-neutrino oscillations fo various values of $\tan^2\theta_{13}$. The global best fit point is marked by the star.

NEAR-FUTURE (i.e. APPROVED) EXPERIMENTS

"ATMOSPHERIC" [VERY BRIEF]

K2K → MINOS – "SEE" OSCILLATIONS
K2K → CNGS – τ-APPEARANCE

} START: 2005/2006

- BOTH WILL MEASURE THE "ATMOSPHERIC PARAMETERS"

$\sin^2 2\theta_{23}$, $|\Delta m^2_{13}|$ WITH $\mathcal{O}(10\%)$ ACCURACY

- IMPROVE ON $|U_{e3}|^2$ SEARCHES BY FACTOR $\mathcal{O}(2)$

"SOLAR" → SENSITIVE TO $tg^2\theta_{12}$, Δm^2_{12}

BOREXINO → - STUDY OF ^7Be SOLAR NEUTRINOS

STARTS SPRING 2003

- LARGE SEASONAL EFFECTS FOR $\Delta m^2 \sim 10^{-10} eV^2$

- LARGE DAY-NIGHT EFFECT FOR $\Delta m^2 \sim 10^{-7} eV^2$

- WILL EXCLUDE OR "PIN-POINT" PARAMETERS OUTSIDE OF LMA

KAMLAND → - LONG BASELINE REACTOR [$\bar{\nu}_e p \to e^+ n$] EXPERIMENT [$L \sim 100 km$]

STARTED JAN 2002. RESULTS (?) IN 3 WEEKS

- FUTURE SUPER BOREXINO (?)

- WILL EXCLUDE OR PIN-POINT PARAMETERS INSIDE OF LMA

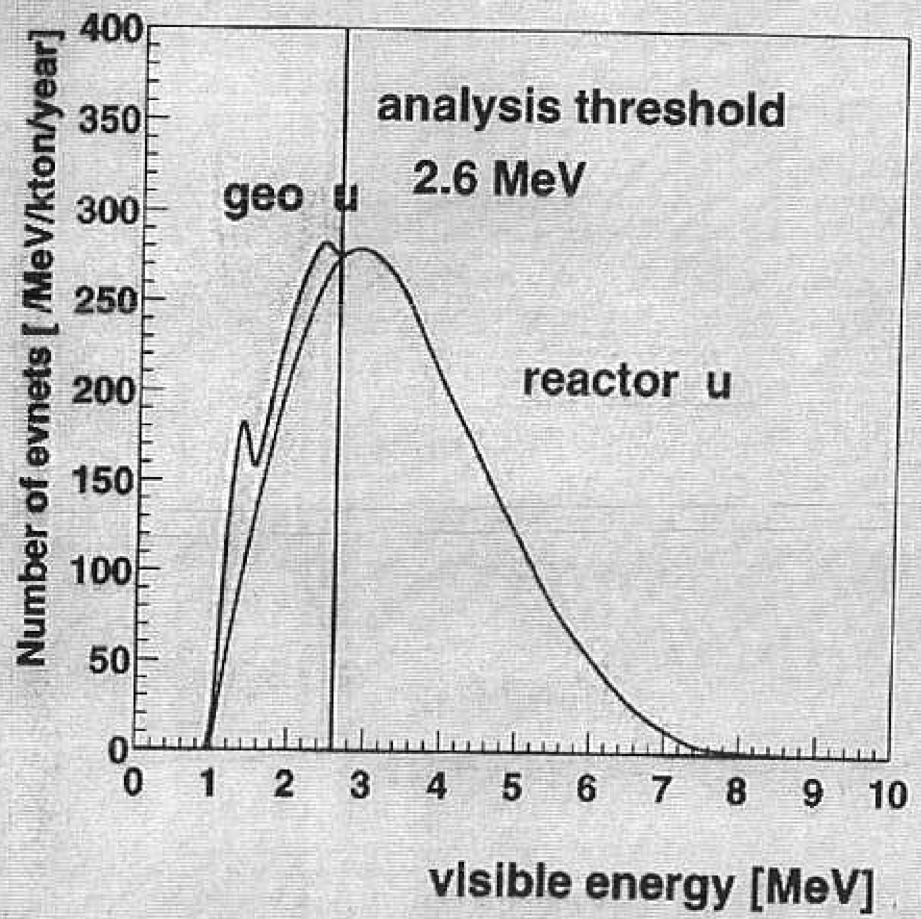
KAMLAND, A REACTOR NEUTRINO EXPERIMENT!

Reactor Site	Distance (km)	# of reactors	Therm. Power (max) (GW)	Max. Flux (10^5 $\bar{\nu}_e$ /cm^2/s)	Max.Event rate events/kt-year
Kashiwazaki	160	7	24.6	4.25	348
Ohi	180	4	13.7	1.90	154
Takahama	191	4	10.2	1.24	102
Hamaoka	214	4	10.6	1.03	84
Tsuruga	139	2	4.5	1.03	84
Shiga	81	1	1.6	1.08	89
Mihama	145	3	4.9	1.03	84
Fukushima-1	344	6	14.2	0.53	44
Fukushima-2	344	4	13.2	0.49	40
Tokai-II	295	1	3.3	0.17	14
Shimane	414	2	3.8	0.10	8
Ikata	561	3	6.0	0.08	7
Genkai	755	4	6.7	0.05	4
Onagawa	430	2	4.1	0.10	8
Tomari	784	2	3.3	0.02	2
Sendai	824	2	5.3	0.03	3
Total		51	130	13.1	1075

Table 3: Expected contribution of different reactors to the neutrino rates detected in KamLAND in the case of no oscillations. The event rate in the last column has been calculated assuming no oscillation and 100% "live time" for each reactor. Thermal power, flux and event rates are all given for the maximum operation of the reactors. Typically, annual averages are about 80% of the maximum.

BASELINE: 85.3% OF SIGNAL FROM 140-344 km

$\bar{\nu}_e$ energy spectrum at KamLAND



$\bar{\nu}_e + p \rightarrow e^+ + n$ — e^+ OBSERVED

$\Delta E/E = 5\%/\sqrt{E}$

We can also observe geo $\bar{\nu}_e$.
First obvervation !

However, it is background to reactor $\bar{\nu}_e$ analysis.

$\Downarrow$

$E_{th} = 2.6$ MeV
Reactor $\bar{\nu}_e = 320$ /year
(fiducial 0.5 kt)

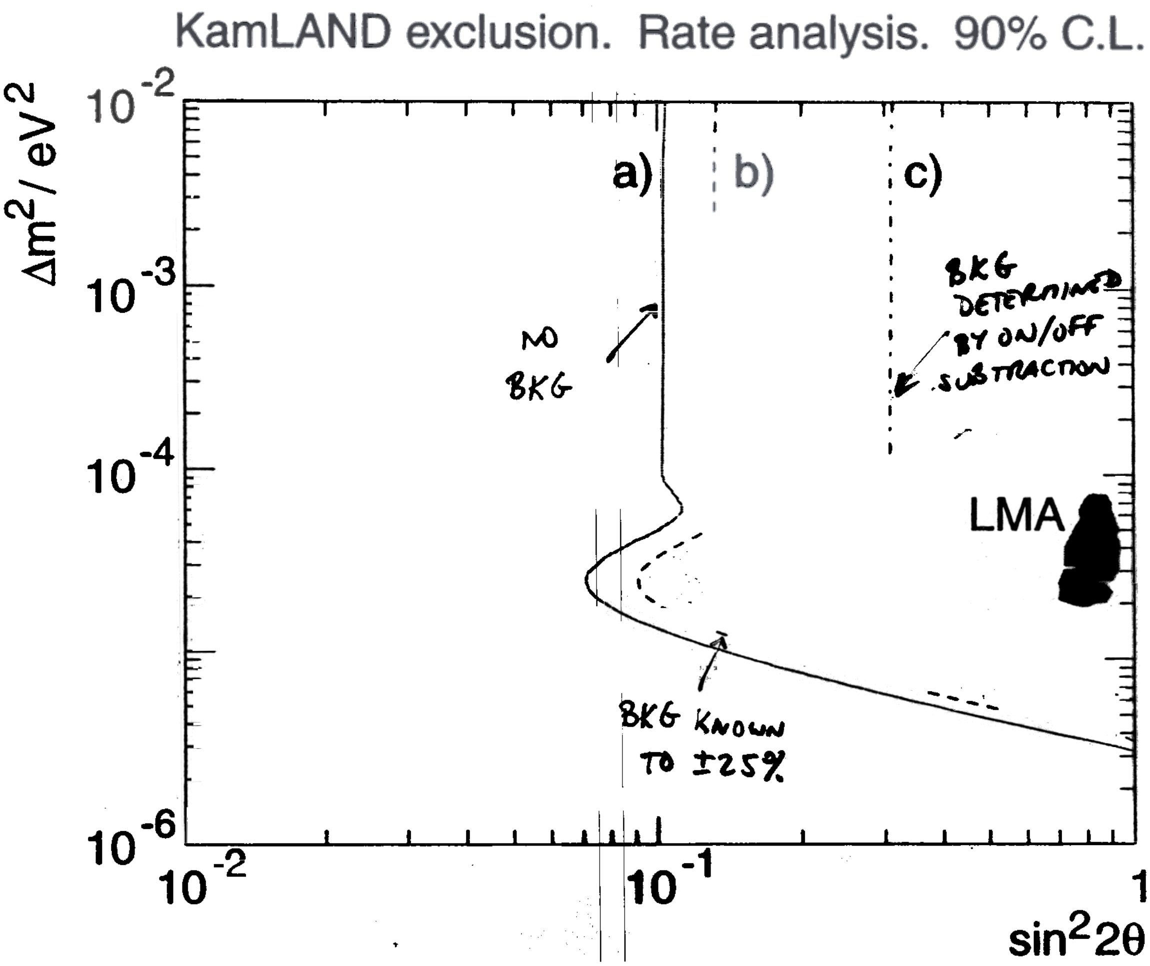


Figure 8: Sensitivity of the neutrino oscillation experiment to be performed at KamLAND. The curves represents the 90% CL sensitivity one can reach with 3 years of running with 78% of the maximum power flux. The following assumptions about the background level and its uncertainty have been made: a) ideal case; no background. b) signal-to-noise 10:1, background known to ±25%. c) signal-to-noise 10:1, background determined by subtraction through reactor on - off.

AdG + C. PEÑA-GARAY
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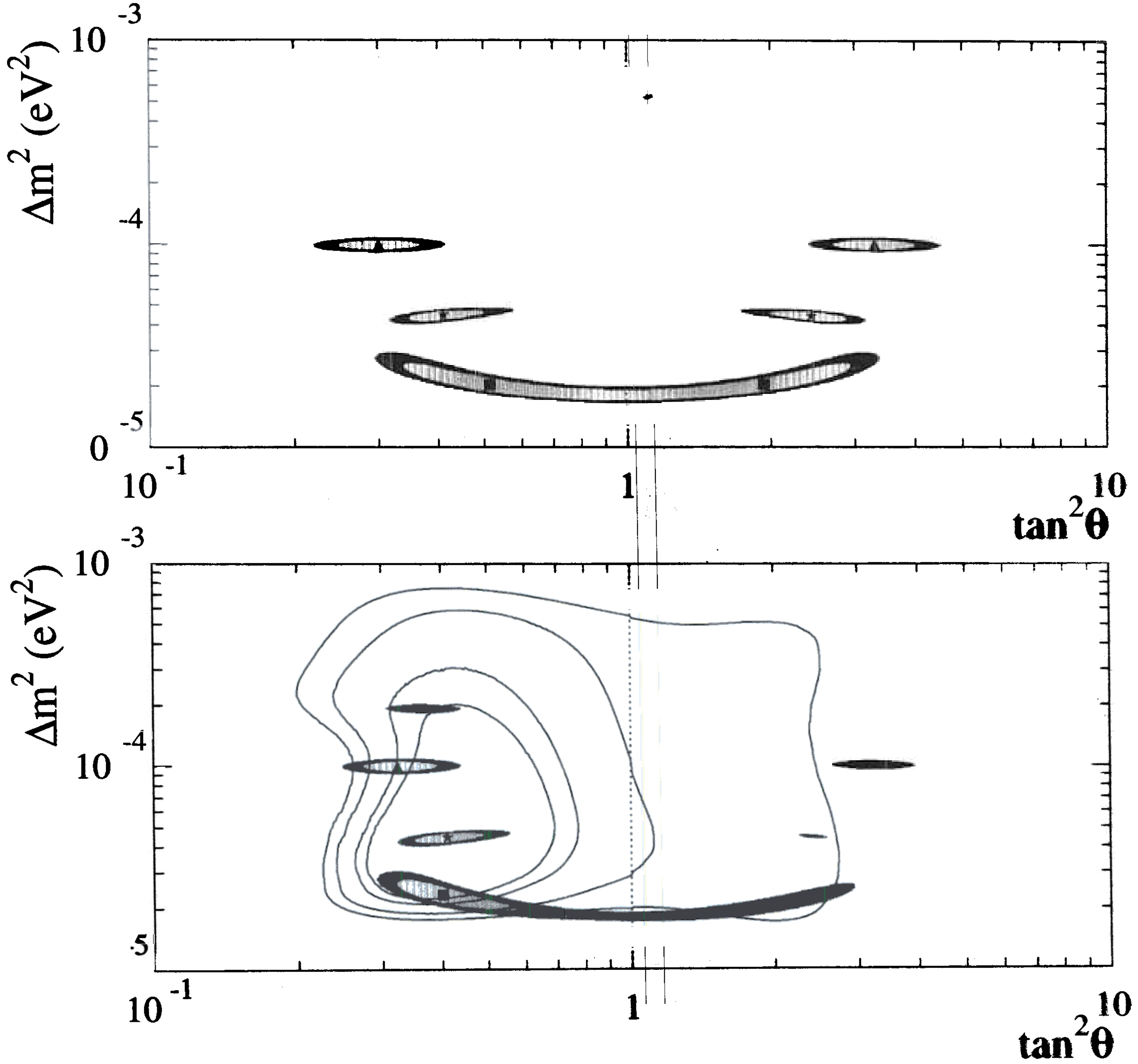


Figure 5: TOP- Region of the $(\Delta m^2 \times \tan^2\theta)$-parameter space allowed by three KamLAND-years of simulated data (see text) at the 90% and three sigma and, for different input values of Δm^2 and $\tan^2\theta$. The different symbols (star, square, circle, etc) indicate the best fit points. BOTTOM- Same as TOP, except that the current solar data is also included in the fit, assuming that the electro-type neutrino oscillates into a pure active state. The line contours indicate the current LMA region, defined for 2 d.o.f., at 90%, 95%, 99%, and three sigma CL.

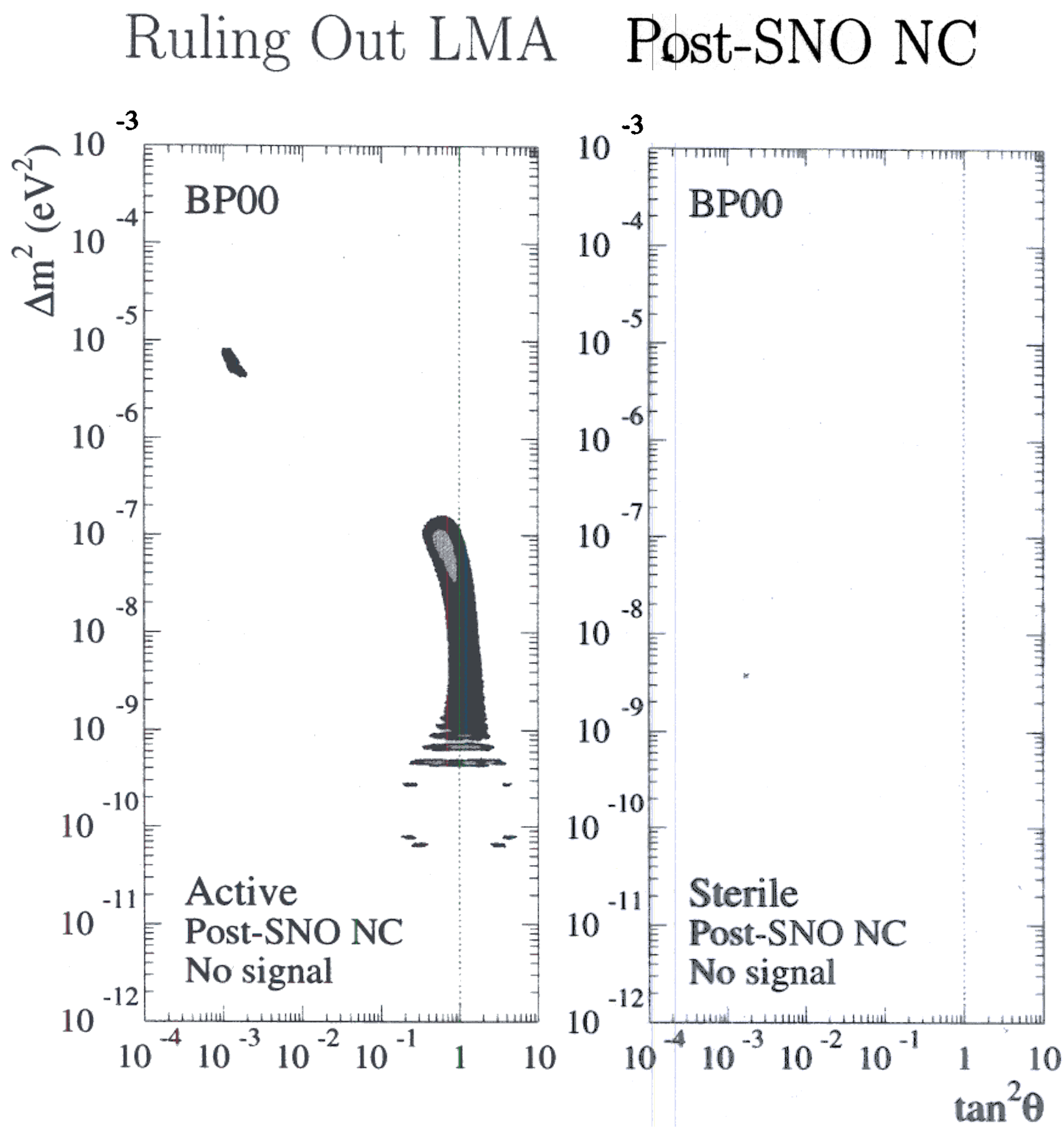
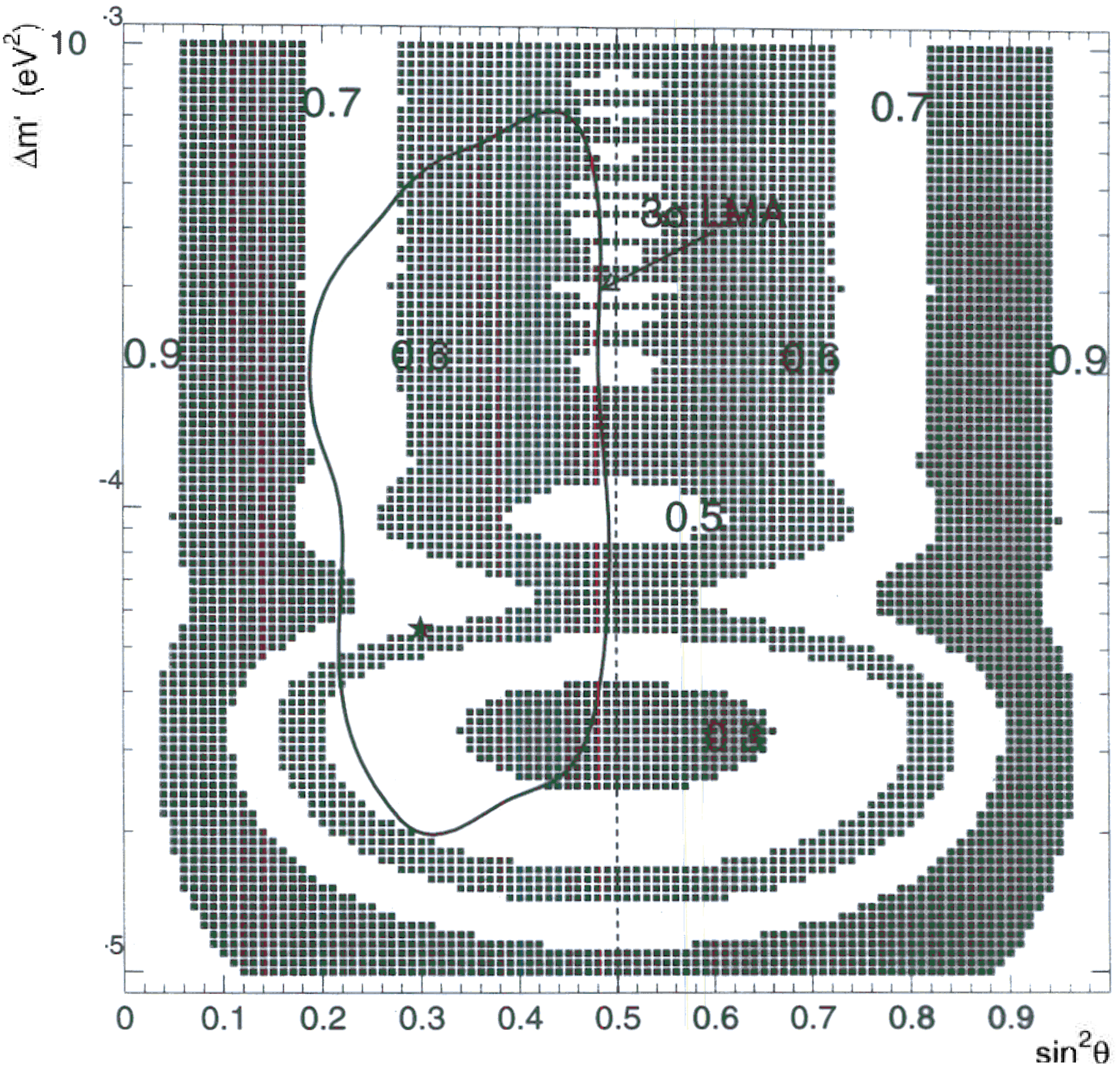


Figure 8: Region of the $(\Delta m^2 \times \tan^2\theta)$-parameter space allowed by the current solar data plus three KamLAND-years of simulated data at the 90%, 95%, 99%, and three sigma CL (for three degrees of freedom), assuming that KamLAND sees no evidence for neutrino oscillations. The left panel is for $\sin^2\zeta = 0$ (pure active oscillations), while the left panel corresponds to $\sin^2\zeta = 1$. The theoretical errors for the BP2000 neutrino fluxes are included in the analysis.

$E_s > 2.6$ MeV



0.7
0.7
3σ LMA
0.9
0.6
0.6
0.9
0.5
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
sin²θ
Δm² (eV²)
10⁻³
10⁻⁴
10⁻⁵