Les Houches, 22 June 01

ν MASSES AND MIXING: Outlook and Perspective

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Neutrino oscillations

Experimental firm points and dilemmas:

- Atmospheric neutrinos:

$\nu_\mu \dashrightarrow \nu_\tau$ dominant, $\nu_\mu \dashrightarrow \nu_e$ small,
$|U_{13}|<0.2$ (CHOOZ), , $\nu_\mu \dashrightarrow \nu_{sterile}$ small
$\Delta m^2 \sim 2.5\ 10^{-3}\ eV^2$, $\sin^2 2\theta_{23} > 0.88$.

- Solar neutrinos:

$\nu_e \dashrightarrow \nu_{\mu,\tau}$ which solution?
$\Delta m^2 \sim 6\ 10^{-6}\ eV^2$, $\sin^2 2\theta_{12} \sim 10^{-3}$ MSW-SA,
$\Delta m^2 \sim 10^{-4}\ eV^2$, $\sin^2 2\theta_{12} \sim 0.75$ MSW-LA,
$\Delta m^2 \sim 10^{-7}\ eV^2$, $\sin^2 2\theta_{12} > 0.75$ LOW,
$\Delta m^2 \sim 10^{-10}\ eV^2$, $\sin^2 2\theta_{12} > 0.8$ VO.
No direct oscillation signal seen yet.
No fit is really good for rate, spectrum, day-night (MSW-LA now preferred).
Pure $\nu_e \dashrightarrow \nu_{sterile}$ disfavoured.

- LSND true or false??

$\nu_\mu \dashrightarrow \nu_e$, $\nu_{sterile}$, $\Delta m^2 \sim 1\ eV^2$, $\sin^2 2\theta \sim$ small.

Near Future of Atmospheric ν's

Main Experiments

- K2K: Aims at confirmation in a terrestrial experiment (is running, preliminary results).

- MINOS: Precise measurements of Δm^2_{23}, $tg^2\theta_{23}$, U_{e3} (start ~2003).

- OPERA: ν_τ appearence experiment (start ~2005)

- ICARUS

- ν Factories

A ~ 2σ EVIDENCE SOFAR

SK event summary

Summary through end of 2000 run:

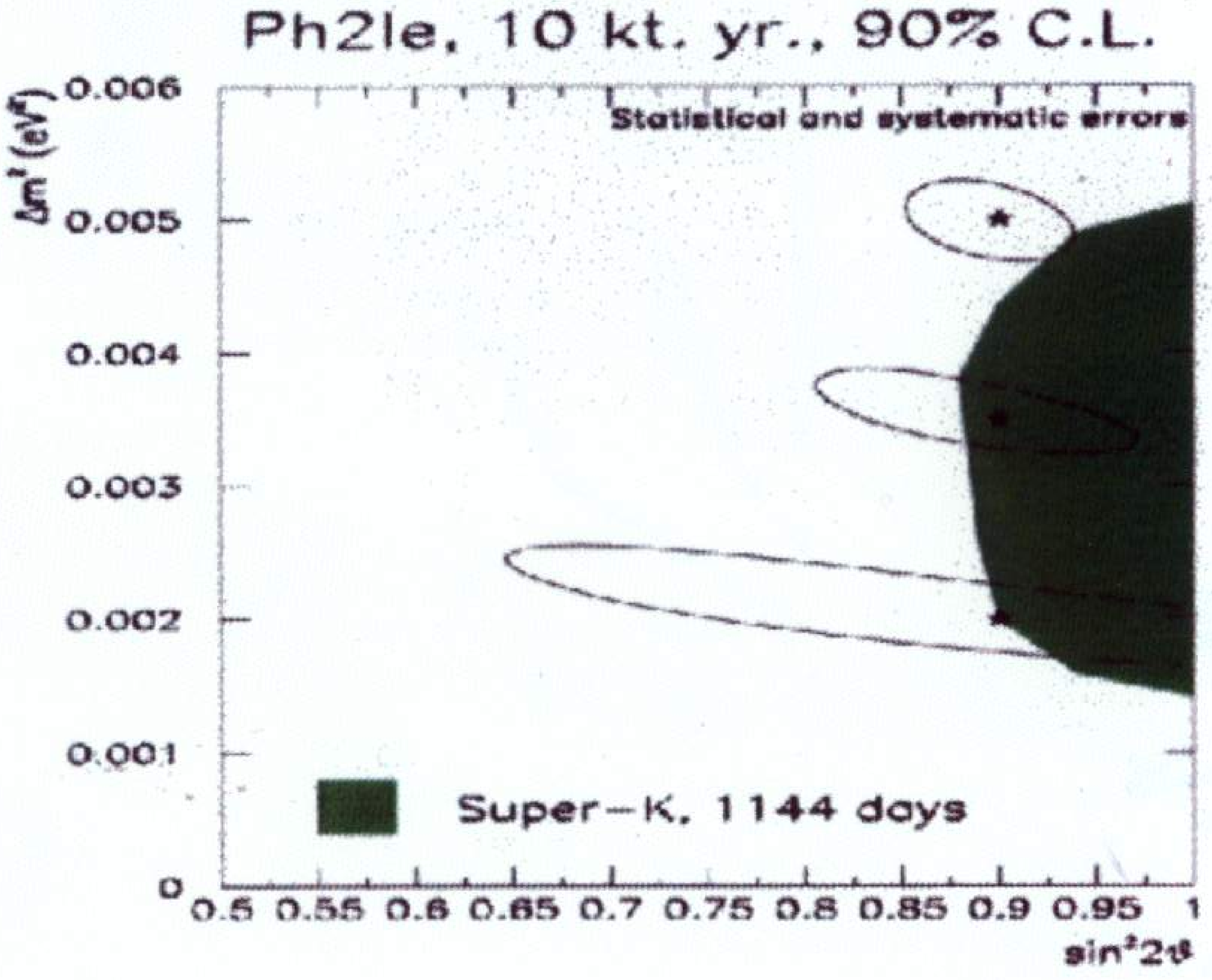
- Superk livetime for FC events: 2.25 x 10^{19} pot
- Events observed vs expected (from 1 kT data):

Event type (FC, inside fid.vol.)	SK Observed	SK Expected (no osc)	SK Expected ($\Delta m^2 = 3 \times 10^{-3}$ eV^2)
1-ring Mu-like	14	20.8 ± 3.2	11.7 ± 1.9
1-ring e-like	1	1.9 ± 0.4	1.6 ± 0.3
Multi-ring	13	15.1 ± 2.5	11.4 ± 2.0
Total	28	$37.8^{+3.5}_{-3.8}$	24.7 ± 2.7

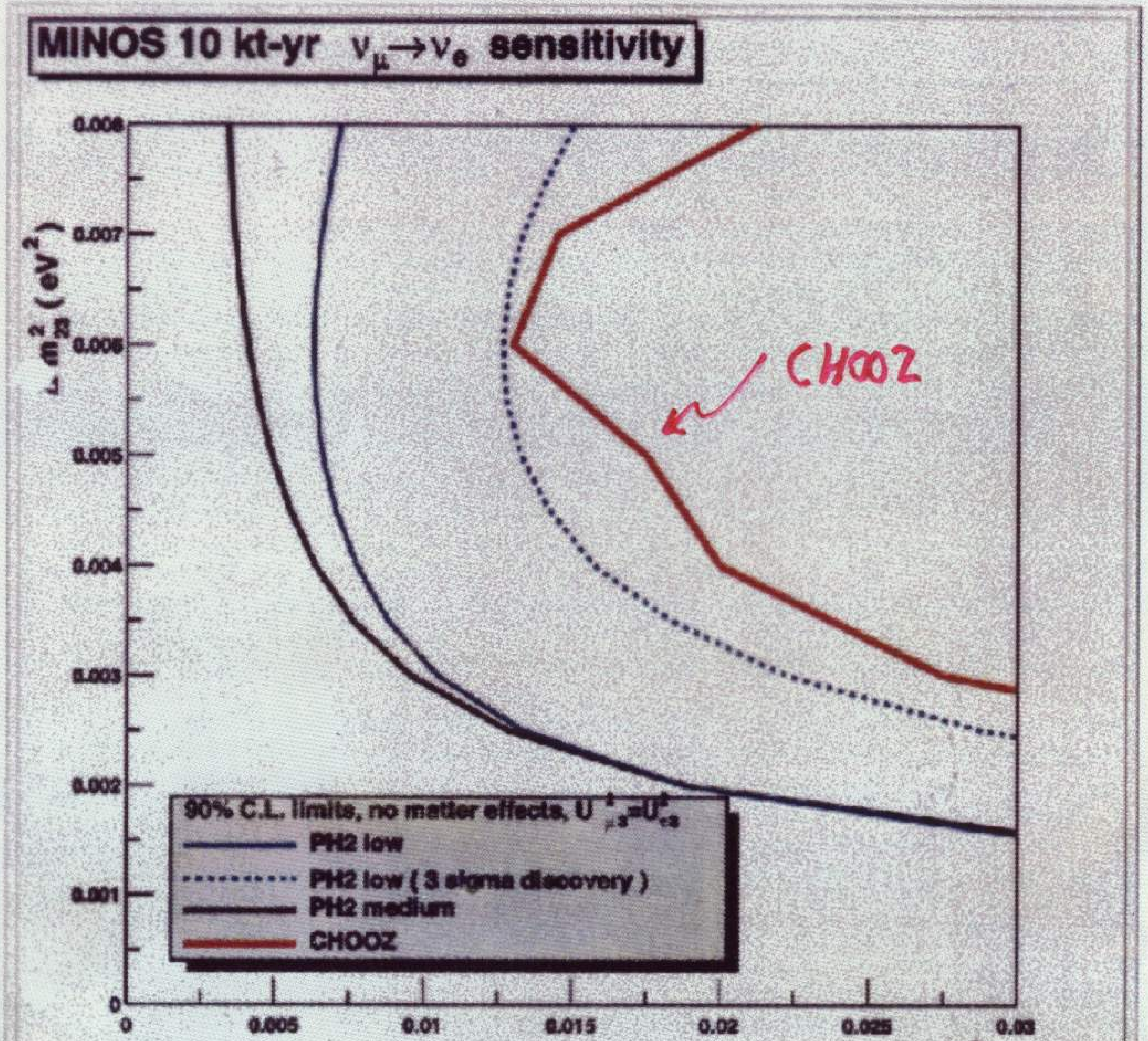
- Comparison of predicted total events (no-osc) from individual near detector subsystems:

KEK detector used for extrapolation	SK expected (no osc)
1 kT	37.8 $\pm$ 3.6
Sci-Fi	37.2 $\pm$ 7.3
Muon detector	41.0 $\pm$ 7.0

MINOS Sensitivity from CC



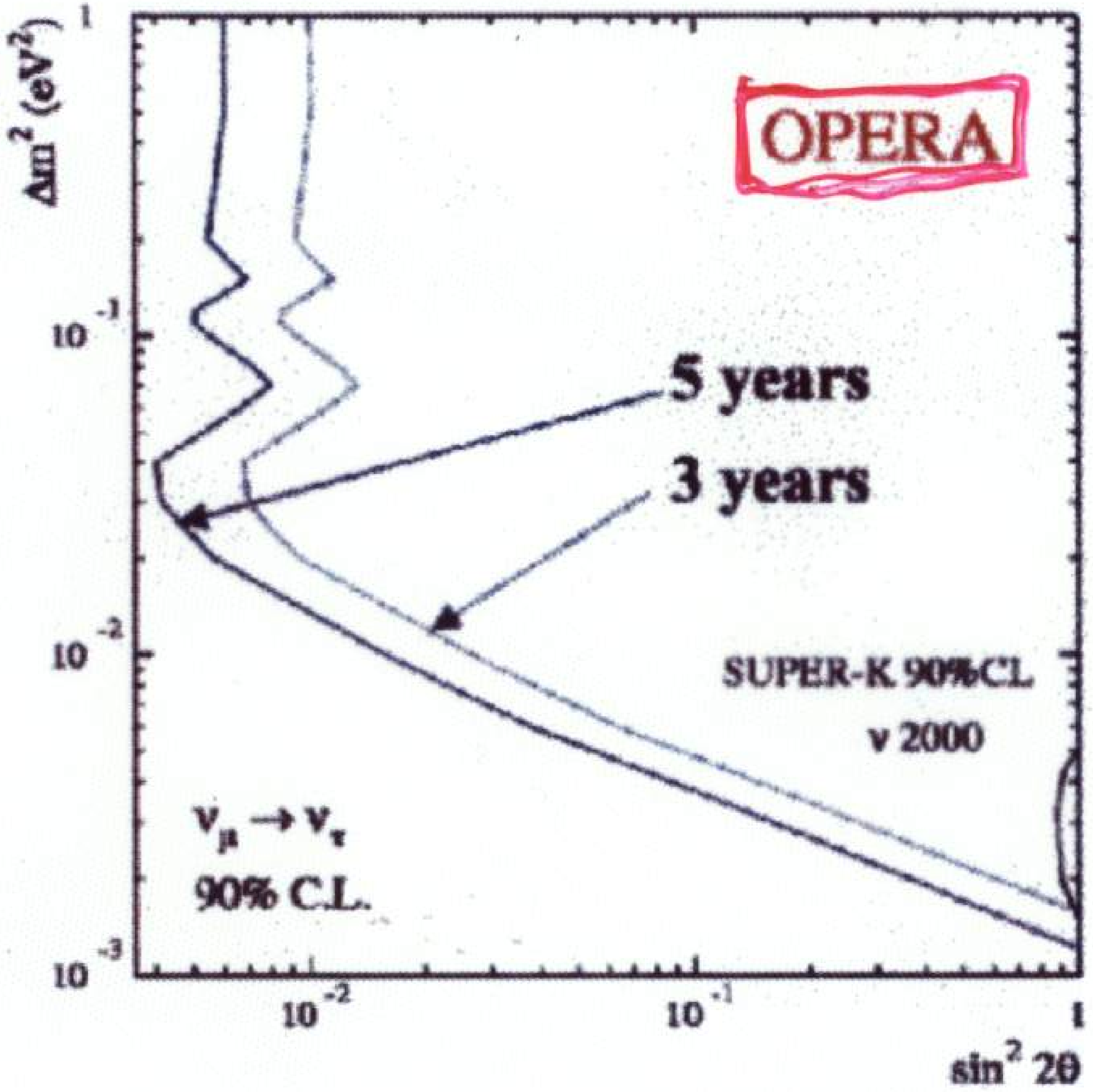
$\nu_\mu \to \nu_e \ : |U_{e3}|^2$



ν_τ APPEARENCE

Sensitivity

(average 90 % CL upper limit for a large number of exp.ts in the absence of a signal)



$\gtrsim$ 2005

5 years data taking

$\Delta m^2 = 1.2\times10^{-3}$ eV^2 at full mixing

$\sin^2(2\theta) = 6.0\times10^{-3}$ at large Δm^2

Near Future of Solar ν's

Experimental Situation Now Unclear:

- No Oscillations Directly Observed
- Many Solutions

Main Experiments

- SNO: Can discriminate solutions by measuring CC, NC and ES. First results now published!
- KAMLAND: Sensitive to LMA region. Can establish this solution and measure Δm^2_{12} and $tg^2\theta_{12}$ (start 2001).
- BOREXINO: Sensitive to ^{7}Be component (start ~2002).

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 $\Rightarrow$ 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)

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

NEW: $\phi_e + \phi_{\mu+\tau} \sim$ SSM

BUT $\phi_e \sim \frac{1}{2} \phi_{\mu+\tau}$

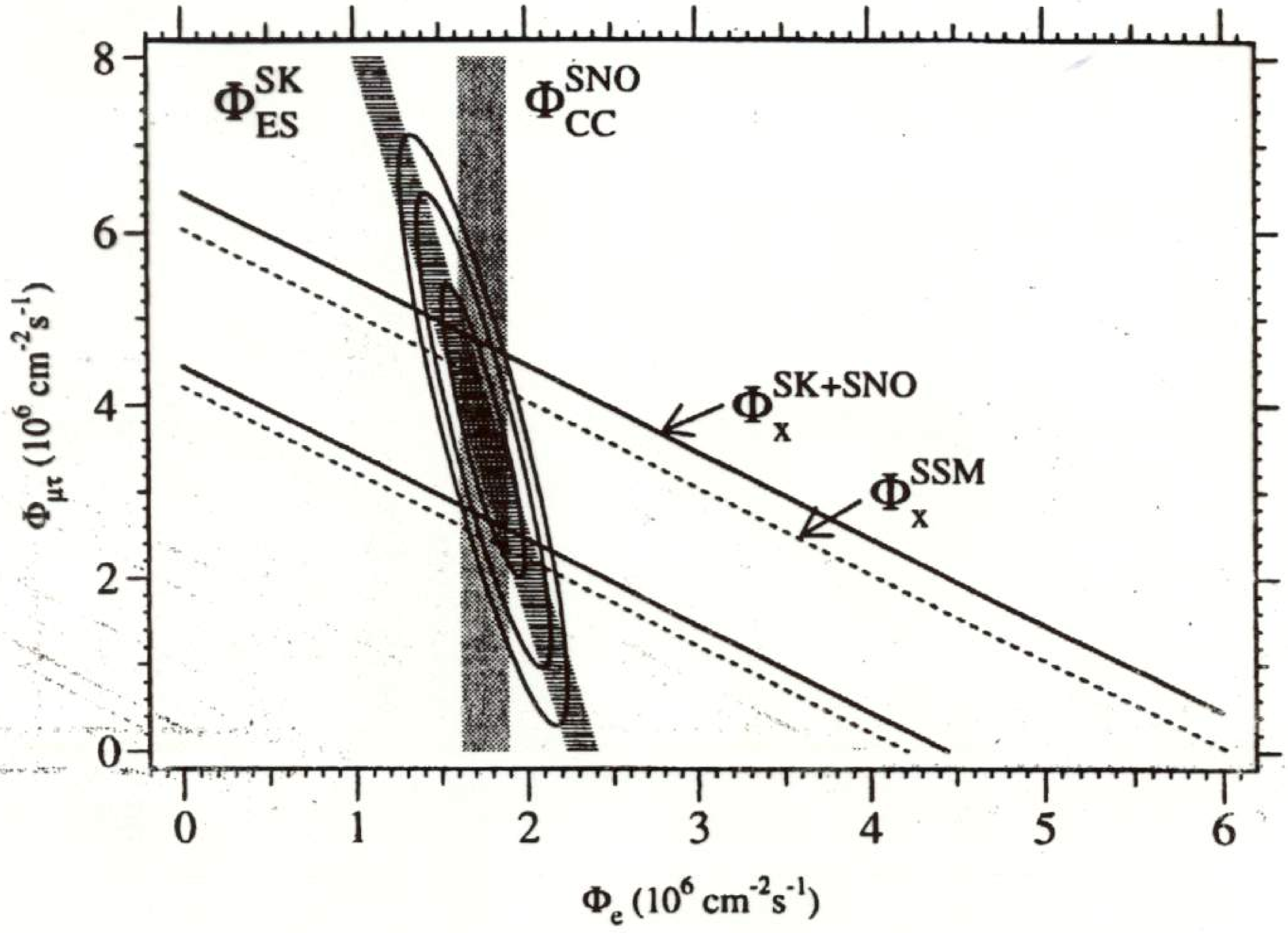
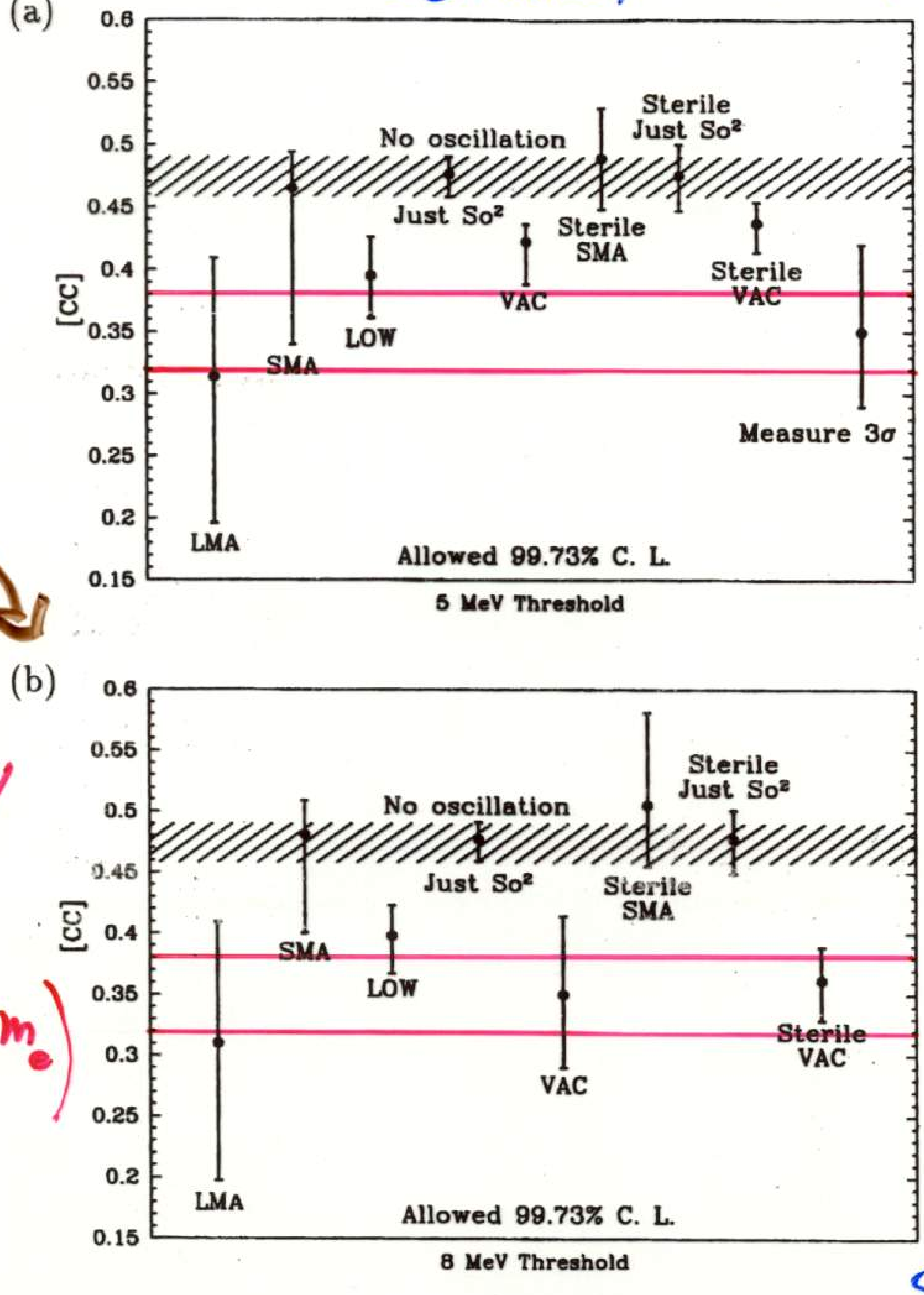


FIG. 3. Flux of ^{8}B solar neutrinos which are μ or τ flavor vs. the flux of electron neutrinos as deduced from the SNO and Super-Kamiokande data. The diagonal bands show the total ^{8}B flux $\phi(\nu_x)$ as predicted by BP2001 (dashed lines) and that derived from the SNO and Super-Kamiokande measurements (solid lines). The intercepts of these bands with the axes represent the $\pm 1\sigma$ errors.

Bahcall, Krastev, Smirnov



5 MeV Thr

SNO DATA

≈7.25 MeV Thr.

$(E_{eff} = T_{eff} + m_e)$

8 MeV Thr

Figure 6: Comparison of the CC SNO rate and the no oscillation prediction. The shaded area is the no oscillation prediction based upon the measured Super-Kamiokande rate for $\nu - e$ scattering. The SNO CC ratios, [CC] = (to be measured)/(BP2000), are shown on the vertical axes for different neutrino scenarios and two different total electron energy thresholds, 5 MeV and 8 MeV. The error bars on the neutrino oscillation results represent the range of values predicted by the 99.73% CL allowed neutrino oscillation solutions displayed in Fig. 1.

BKS

hep, ^{8}B
FLUXES
FREE

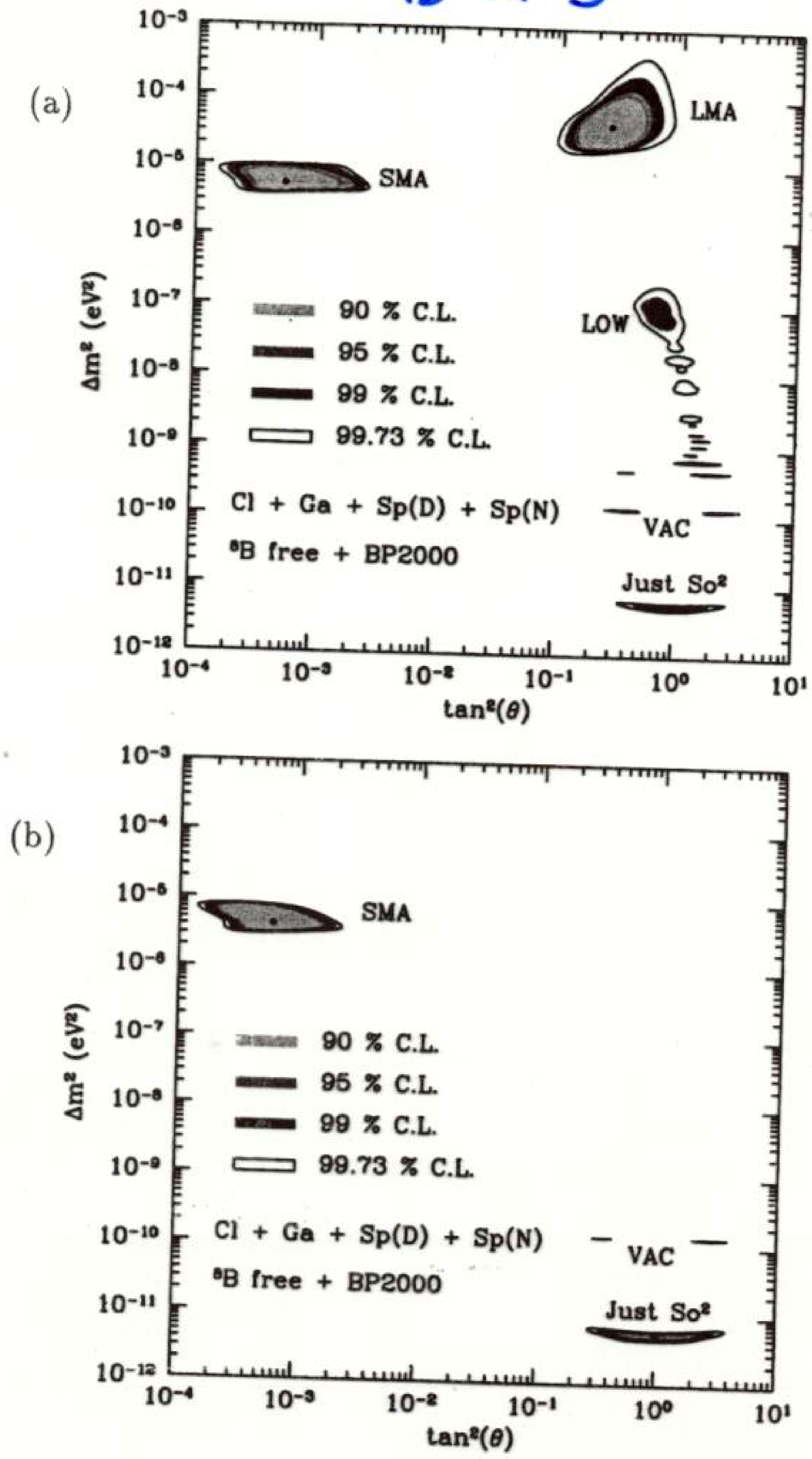


Figure 1: Global solutions, free ^{8}B and *hep* fluxes. (a) Active neutrinos. (b) Sterile neutrinos. The input data include the total rates measured in the Homestake, SAGE, and GALLEX + GNO experiments and the electron recoil energy spectrum measured by Super-Kamiokande during the day and also the spectrum measured at night. The best-fit points are marked by dark circles; the allowed regions are shown at 90%, 95%, 99%, and 99.73% C.L. .

NO DEVIATION IN SHAPES
WrO NO OSCILLATIONS.

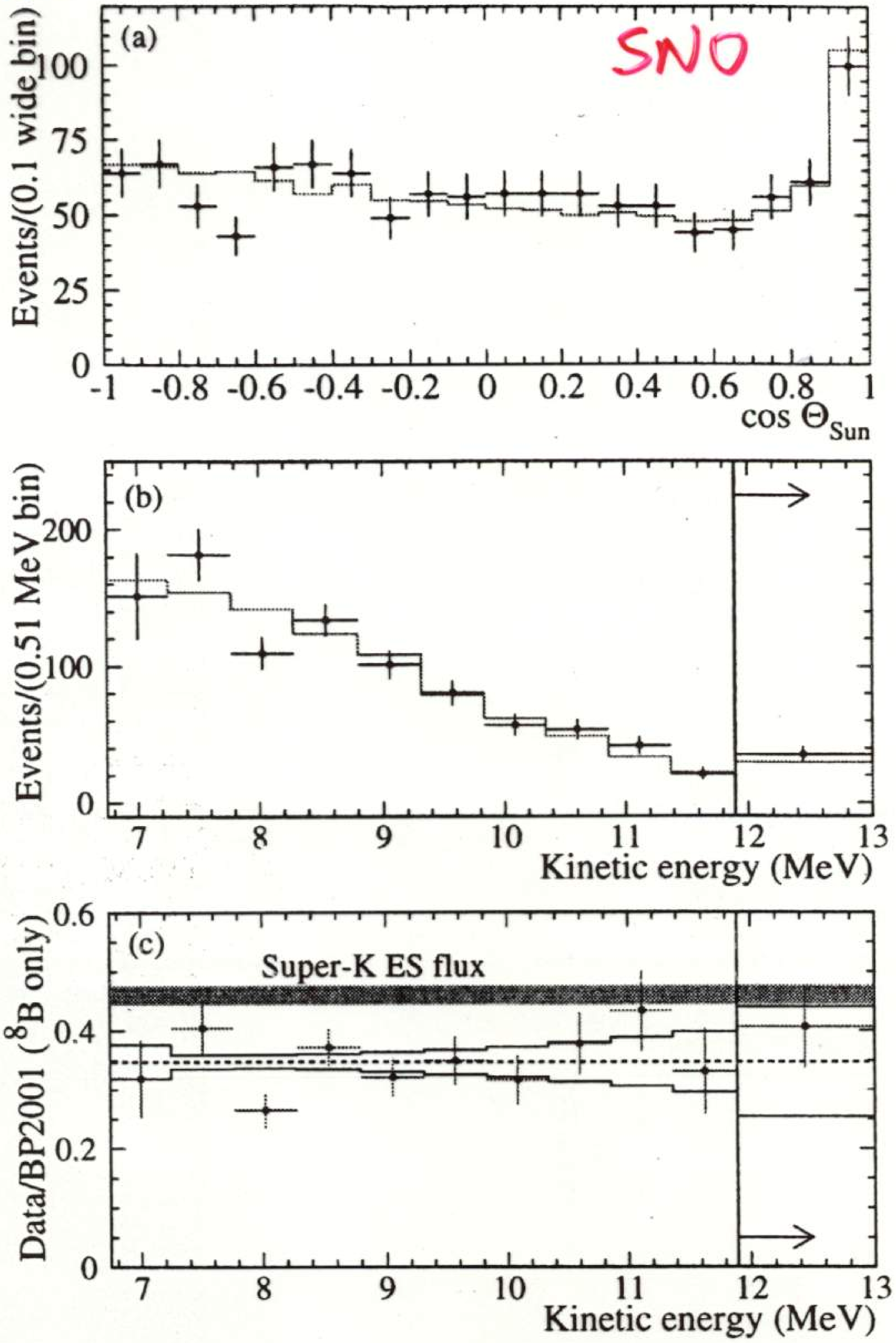


FIG. 2. Distributions of (a) $\cos\theta_\odot$, and (b) Extracted kinetic energy spectrum for CC events with $R \leq 5.50$ m and $T_{\rm eff} \geq 6.75$ MeV. The Monte Carlo simulations for an undistorted ^{8}B spectrum are shown as histograms. The ratio of the data to the expected kinetic energy distribution with correlated systematic errors is shown in (c).

sources of systematic uncertainty in this signal extrac-

BUT MOST SURVIVAL PROBABILITIES ARE FLAT IN THE REGION OF DATA

Bahcall et al

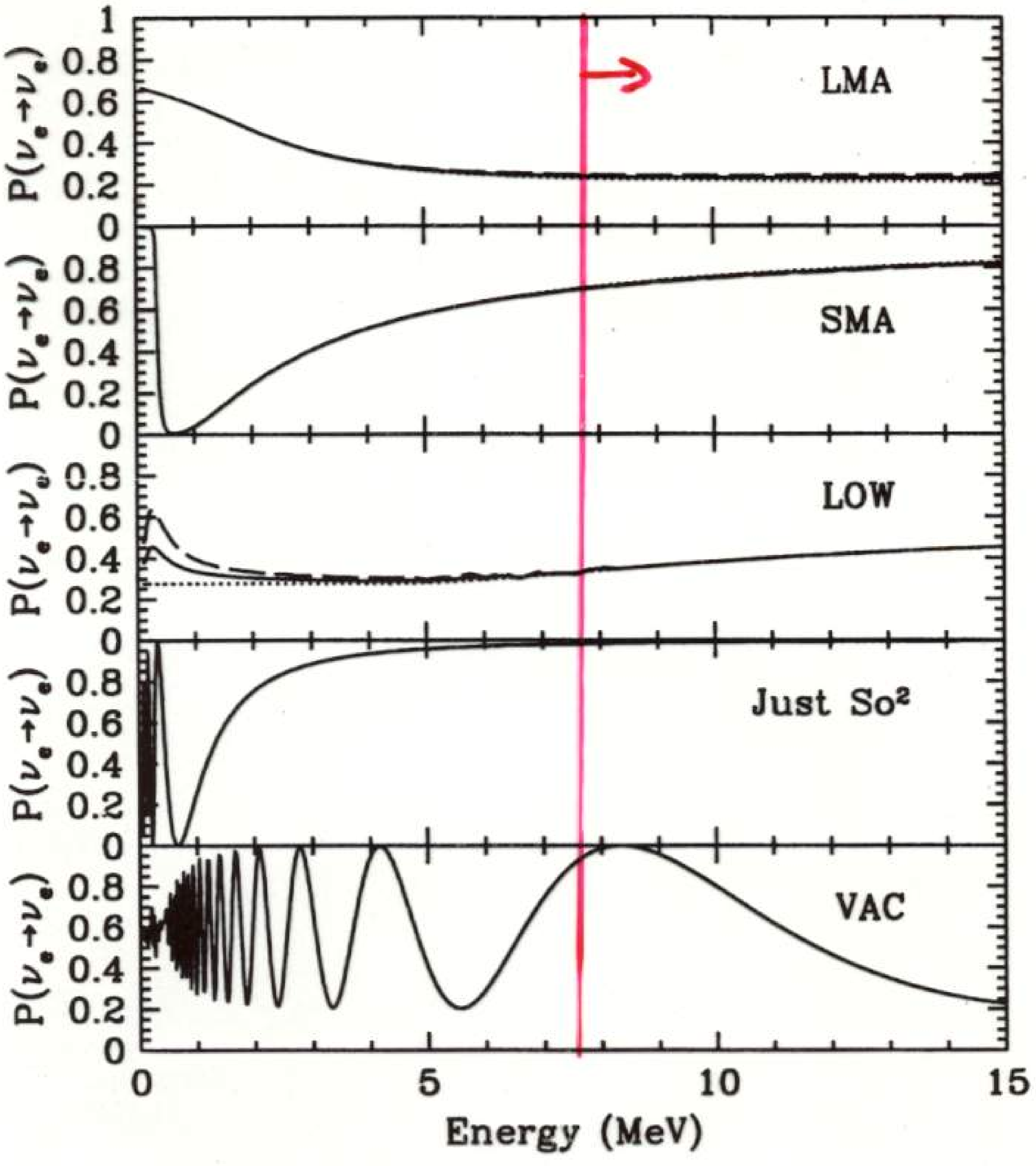


Figure 2: Survival probabilities. The figure presents the yearly-averaged, best-fit survival probabilities for an electron neutrino that is created in the sun to remain an electron neutrino upon arrival at the earth. The survival probabilities for the sterile solutions, SMA, Just So^2, and SMA, are very similar to their counterparts for active neutrinos and are not plotted here. The full line refers to the average survival probabilities computed taking into account regeneration in the earth and the dotted line refers to calculations for the daytime that do not include regeneration. The dashed line includes regeneration at night. There are only slight differences between the computed regeneration probabilities for the detectors located at the positions of Super-Kamiokande, SNO and the Gran Sasso Underground Laboratory (see ref. [25]).

An interesting indicative analysis

Barger, Marfatia, Whisnant

H: High=^{8}B,hep   Norm. Uncert. 18.0%
I: Interm.=^{7}Be, pep, ^{15}O, ^{13}N   11.6%
L: Low=pp   1.0%

$$0.337\pm0.030=R_{Cl}=0.764\beta_H P_H+0.236P_I$$
$$0.584\pm0.039=R_{Ga}=0.096\beta_H P_H+0.359P_I+0.545P_L$$
$$0.459\pm0.017=R_{SK}=\beta_H P_H+0.171\sin^2\alpha(1-P_H)\beta_H$$
$$0.347\pm0.027=R^{CC}{}_{SNO}=\beta_H P_H$$

R: Rates normalized to SSM
β_H: Rescaling of H norm. wro SSM
P_i: Probabilities for ν_e<--> ν_e
$\sin^2\alpha$: fraction into active

Taking central values we have:

$\beta_H P_H=0.347$; $P_I=0.305$; $P_L=0.810$

If we add $\beta_H=1$ ----->$P_H=0.347$, $\sin^2\alpha=1$!

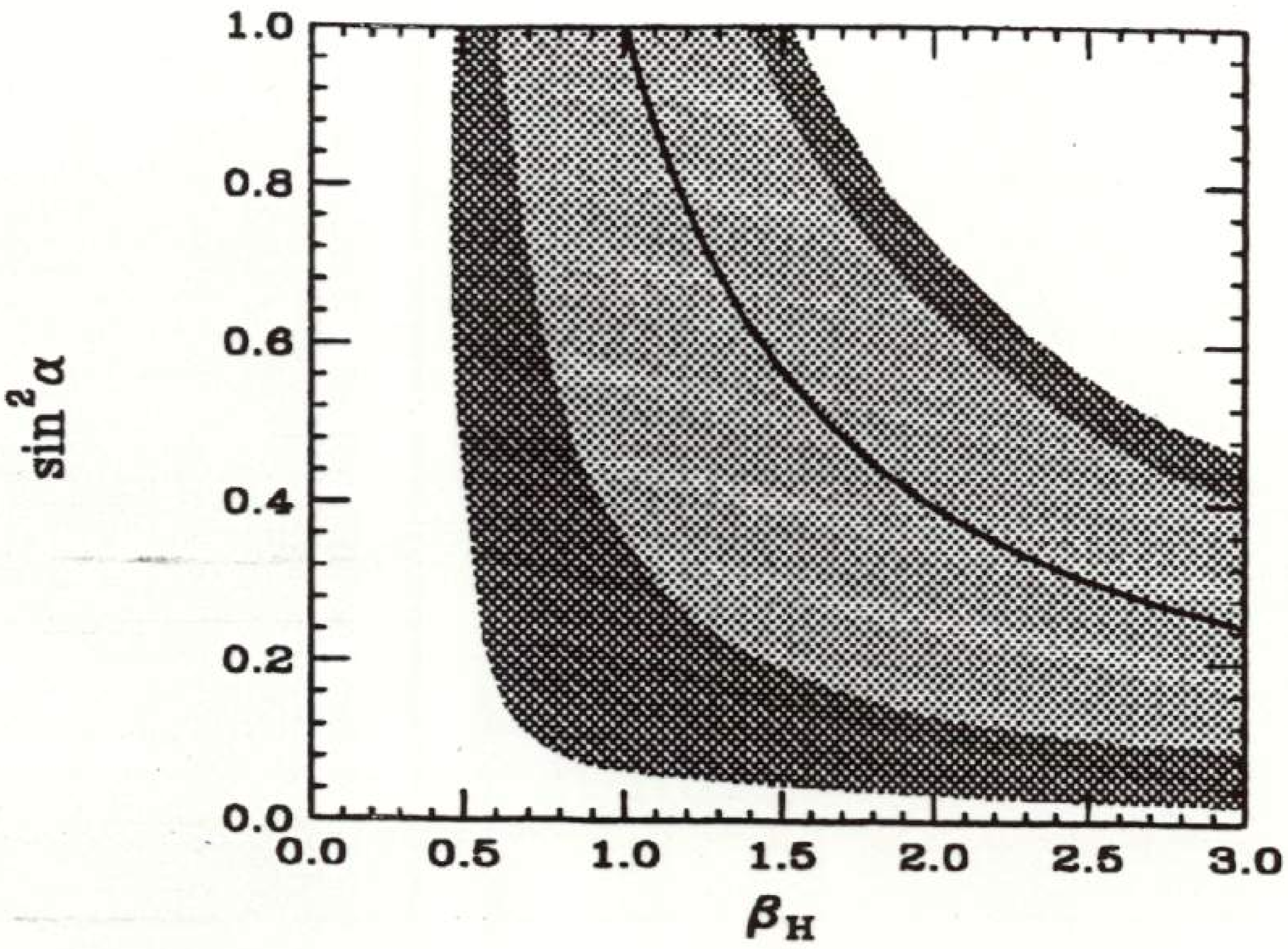
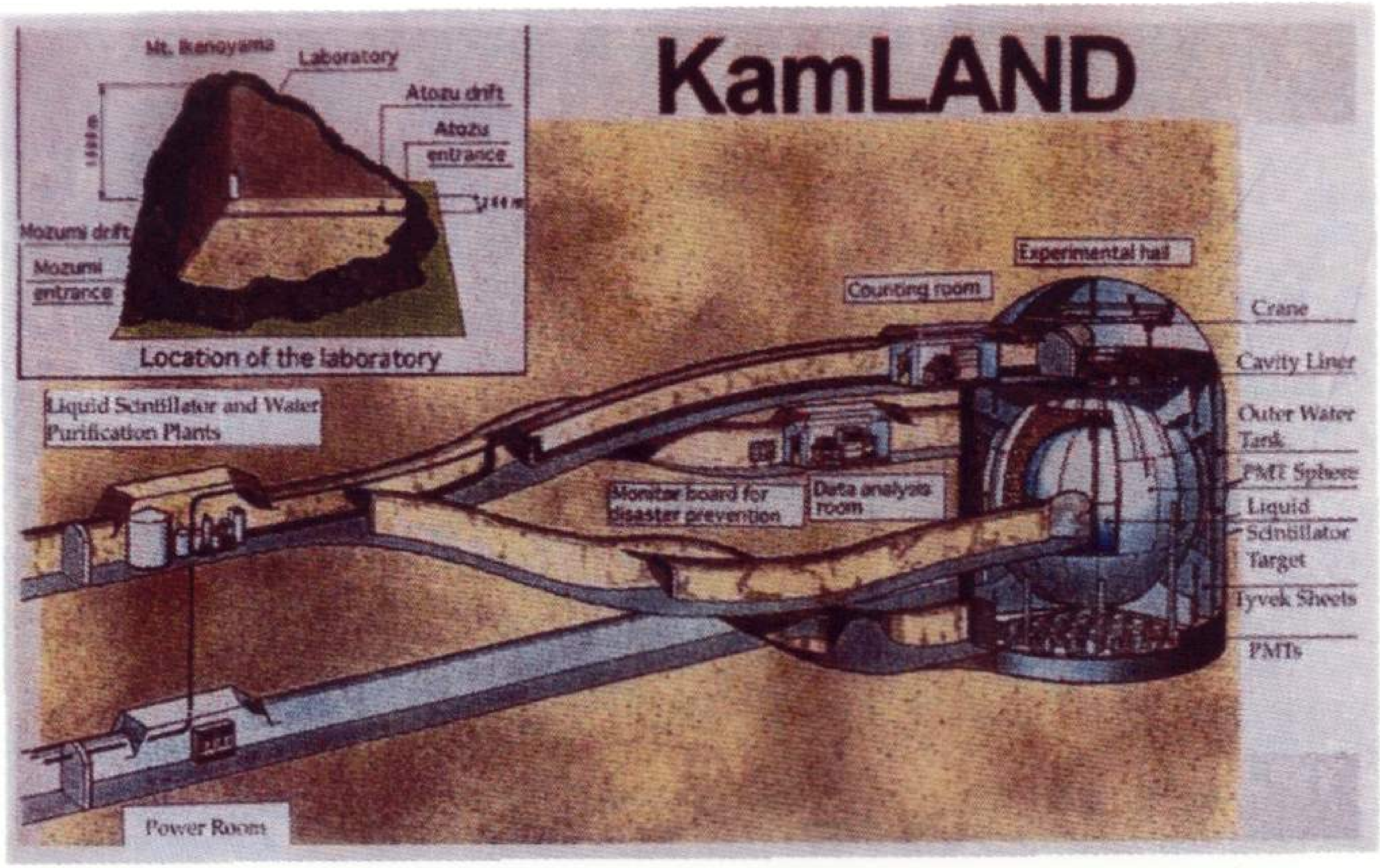


FIG. 1. Active neutrino fraction $\sin^2\alpha$ versus ^{8}B neutrino flux normalization β_H. The line represents solutions with $\chi^2 = 0$, and the 1σ and 2σ allowed regions are shaded.

KamLAND

http://www.awa.tohoku.ac.jp/KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector



long baseline
reactor experiment

converted from
KAMIOKANDE

hosted by
Tohoku University

Filling: Apr. 2001~
Observation: Oct. 2001~

1,000 m^3 liq. scint.
1,300 17-inch PMTs
+600 20-inch PMTs

22+14% coverage

anti: 3,000m^3 water

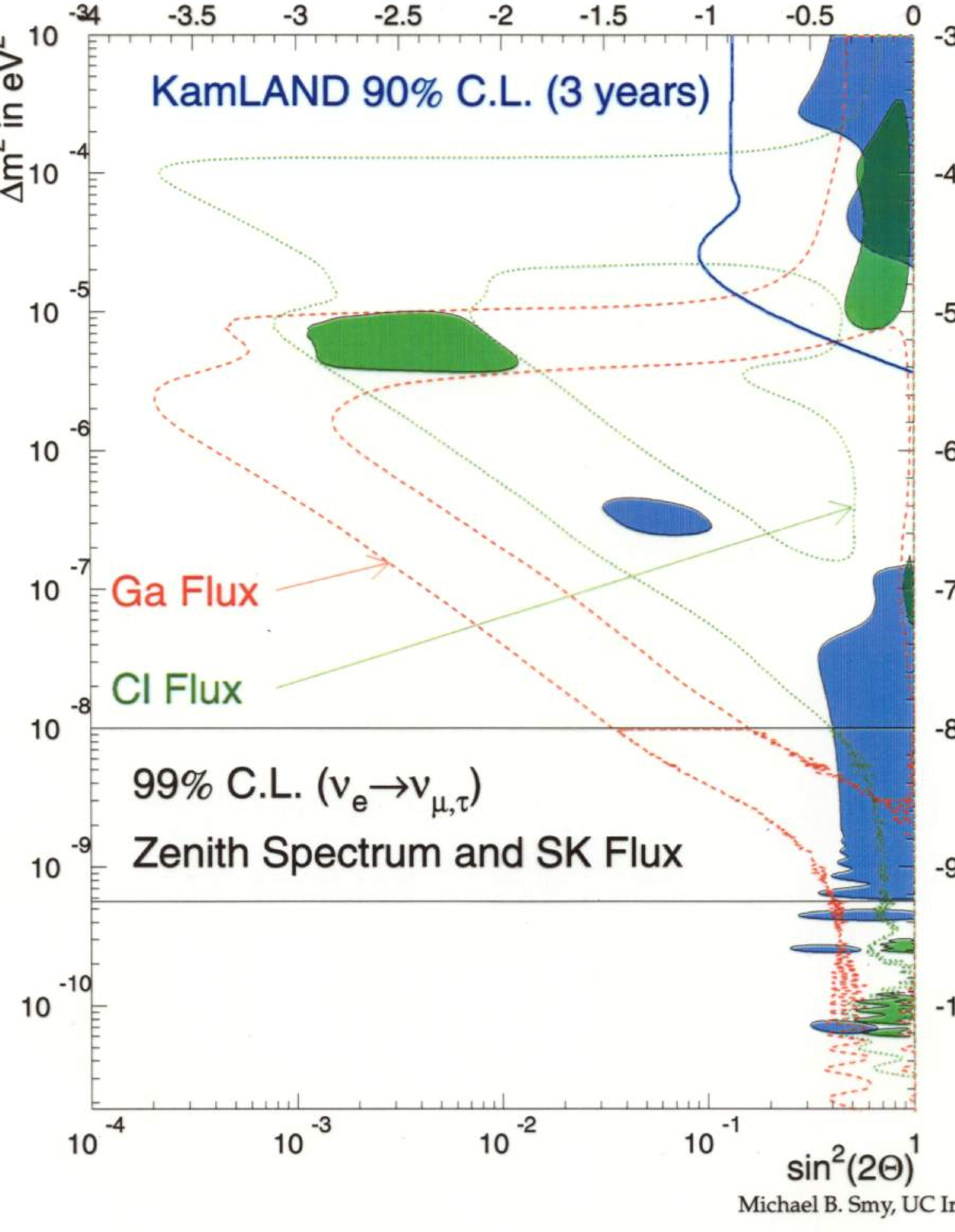
reactor L~170km

700 events/kt/year

$\overline{\nu}_e + p \rightarrow e^+ + n$

(E_{th} = 1.8MeV)

Allowed Regions



Michael B. Smy, UC Irvine

VERY PRECISE MEASUREMENTS OF Δm^2_{12} AND $\sin^2 2\theta_{12}$

Barger, Marfatia, Wood

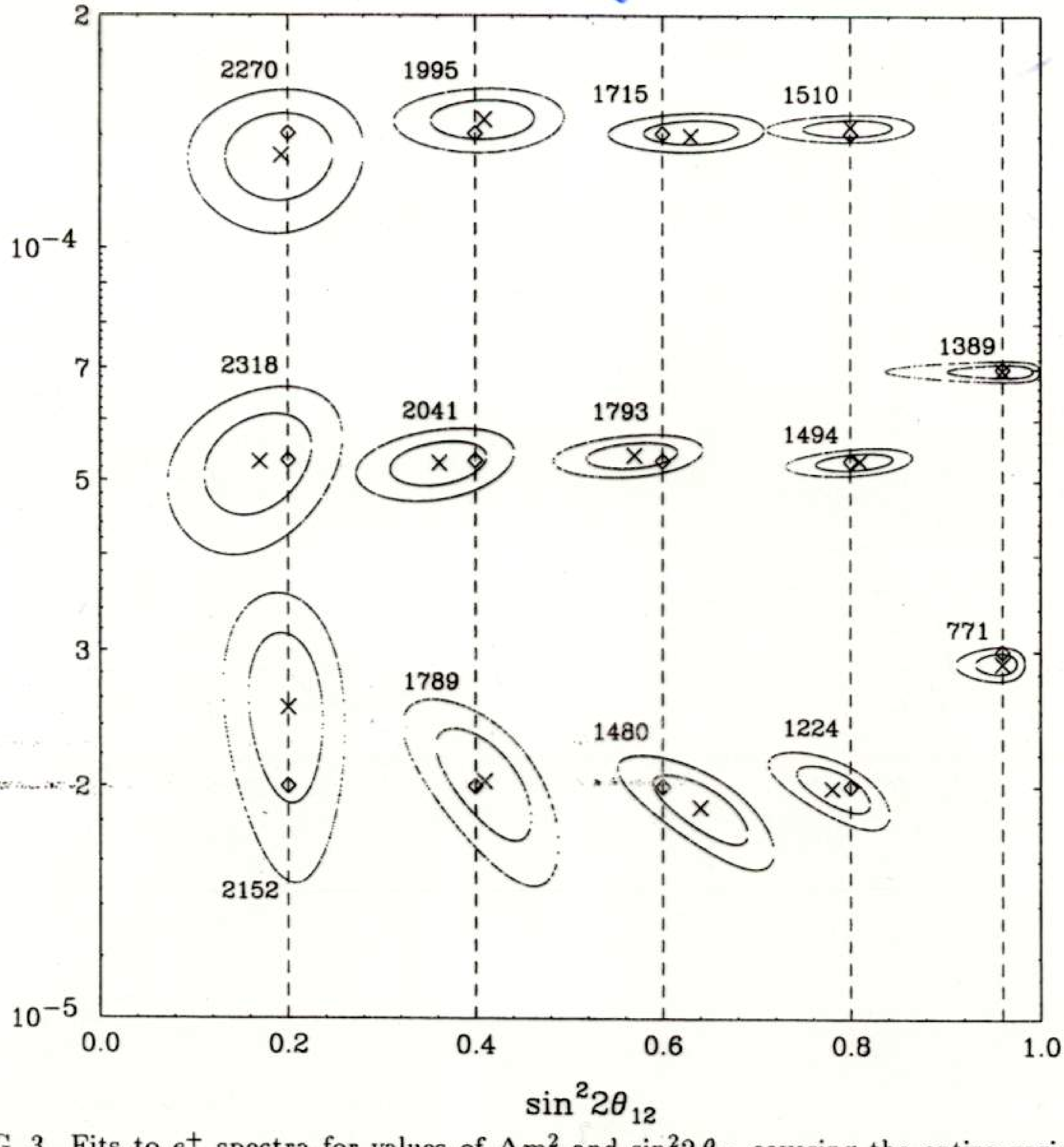
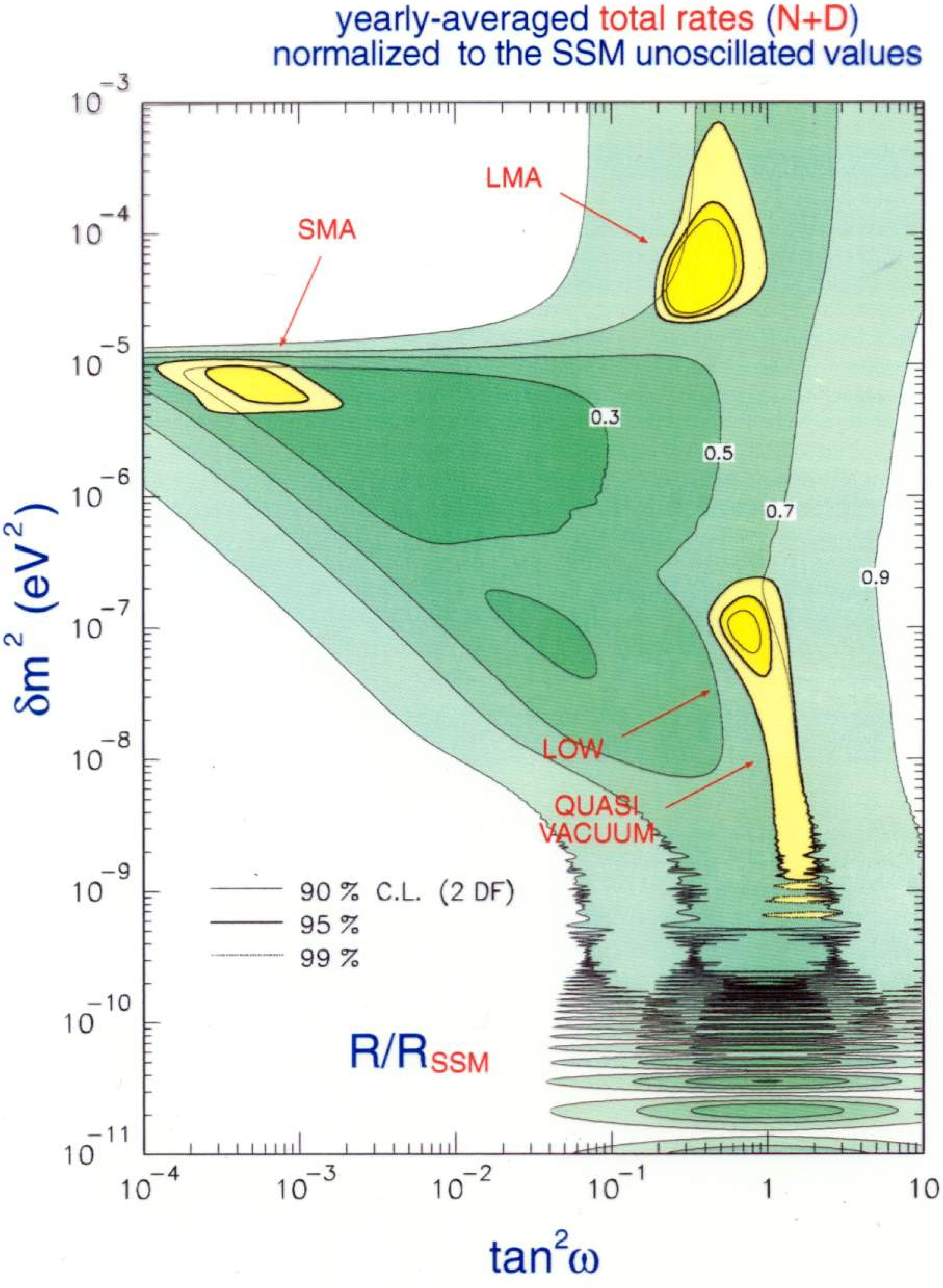
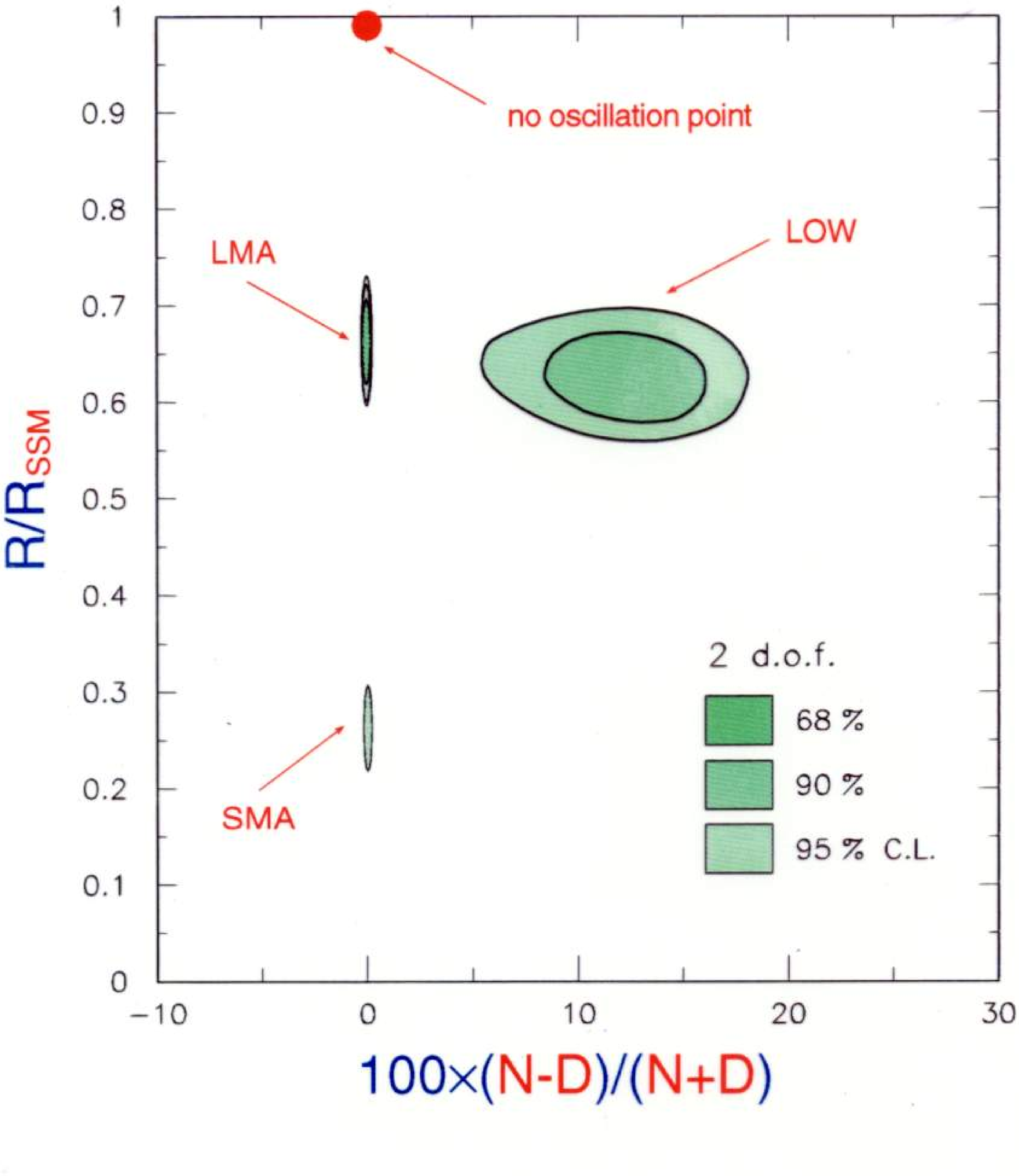


FIG. 3. Fits to e^+ spectra for values of Δm^2 and $\sin^2 2\,\theta_{12}$ covering the entire region of the LMA solution with $\theta_{13} = 0$. The 1σ (68.3%) and 3σ (95.4%) confidence contours are shown. The diamond is the theoretical value for which data was simulated and the cross marks the best fit point. Each point is labelled by the expected number of signal events in three years. If no oscillations occur, the expectation is 2400 events.

Borexino total rates compared with the SMA, LMA and LOW solutions

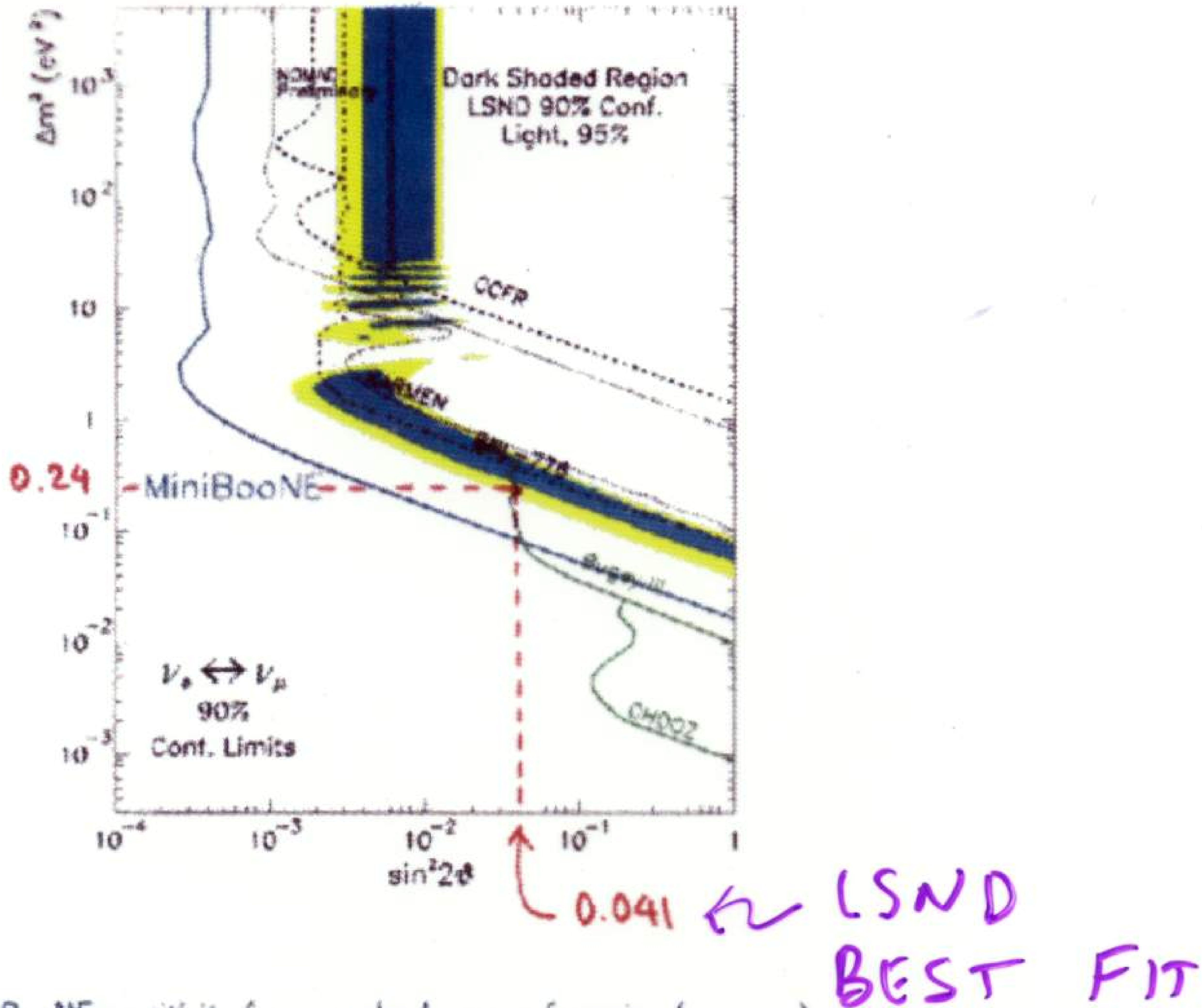


Borexino discovery potential compared with the SMA, LMA and LOW solutions



MINIBOONE [START ~2002]

MiniBooNE Sensitivity:



MiniBooNE sensitivity for one calendar year of running ($\nu_\mu \to \nu_e$)

Neutrino oscillations measure Δm^2

$\Delta m^2_{atm} \sim 2.5\ 10^{-3}\ eV^2$; $\Delta m^2_{solar} < \Delta m^2_{atm}$

- Direct limits

$m"\nu_e" < 2\text{-}3\ eV$
$m"\nu_\mu" < 170\ KeV$
$m"\nu_\tau" < 18\ MeV$

- Cosmology

$\Sigma_i m_{\nu i} \leq \sim 6\ eV$ $[\Omega_\nu \leq \sim 0.2]$

All ν masses ≤ 2 eV

Why ν's so much lighter than quarks and leptons?

Neutrino masses are very small!

- Direct limits
- Cosmological limits (hot dark matter)
- ν oscillation data

----> $m_{\nu i} \leq 1\text{-}2$ eV

or: $m_\nu/m_e \leq 10^{-5}$, $m_\nu/m_t \leq 10^{-11}$

Most appealing explanation:

$$m_\nu \sim m^2/M$$

M: scale of L non conserv. $\sim M_{GUT}\text{-}M_{Pl}$
$m \leq m_t \sim v \sim 200$ GeV

Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV
$m \sim v \sim 200$ GeV

-----> $M \sim 10^{15}$ GeV

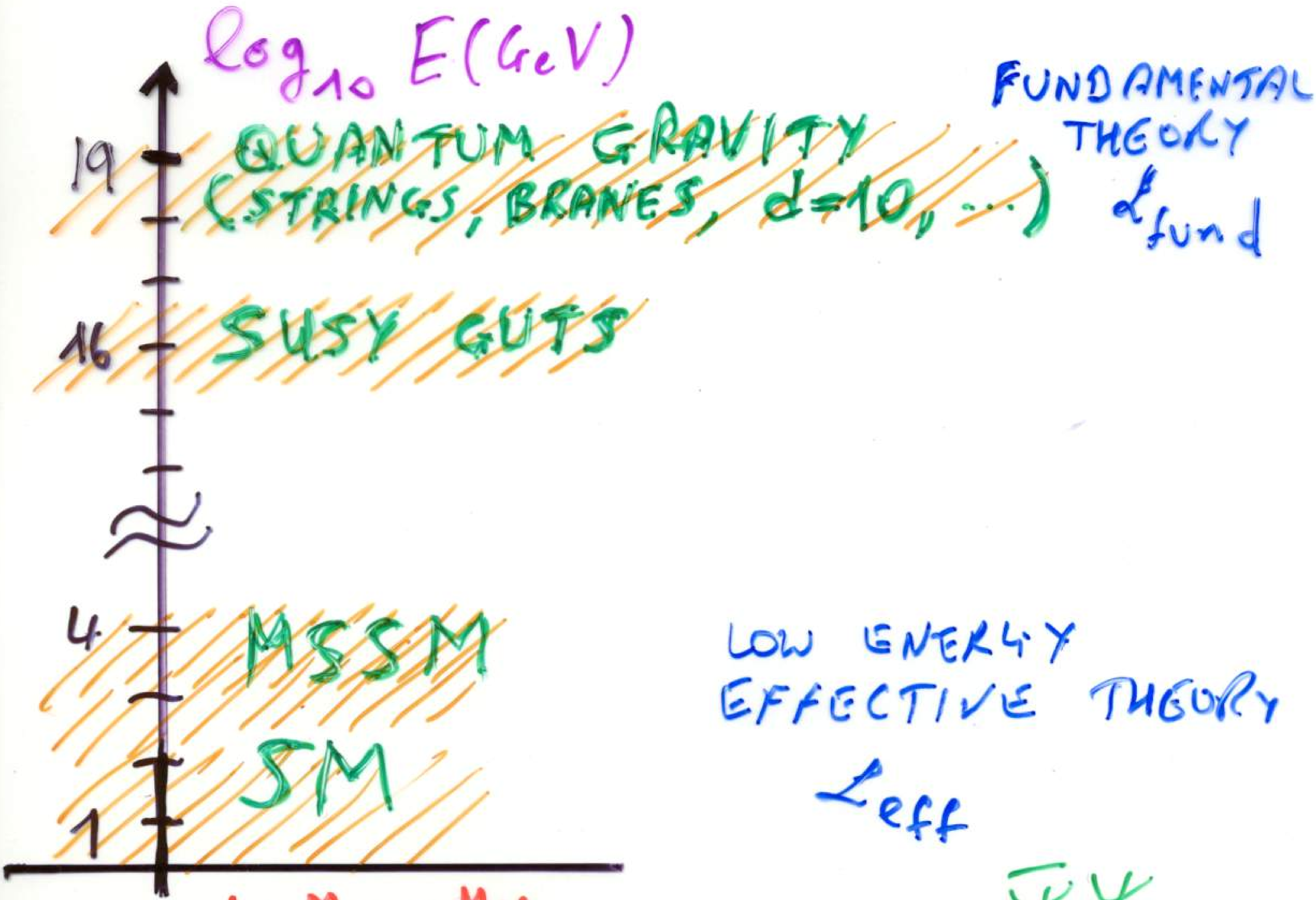
Neutrino masses are a probe of GUT physics!

A very natural and exciting explanation:

ν's are nearly massless because they get masses through Lepton Number non conserving interactions suppressed by a large scale $M \sim M_{GUT}$.

- ν masses are probing the physics near M_{GUT}

- this explanation beautifully fits in a comprehensive picture of the large scale structure of particle physics.



Λ : M_{GUT}, M_{Pl}

$$\mathcal{L}_{eff} \sim O(\Lambda^2)\underbrace{\mathcal{L}_2}_{\sim\varphi^2} + O(\Lambda)\overbrace{\mathcal{L}_3}^{\bar\Psi\Psi} + O(1)\underbrace{\mathcal{L}_4}_{\bar\Psi\gamma^\mu\Psi A_\mu} +$$

$$+ O\left(\frac{1}{\Lambda}\right)\mathcal{L}_5 + O\left(\frac{1}{\Lambda^2}\right)\underbrace{\mathcal{L}_6}_{\bar\Psi\Psi\bar\Psi\Psi} + \dots$$

$\mathcal{L}_n$ IS OF OPERATOR DIMENSION n

$\mathcal{L}_3$: PROTECTED BY $SU(2)\otimes U(1)$, CHIRAL SYMM

$\bar\Psi\Psi$ $\quad O(\Lambda)\mathcal{L}_3 \to m \ln\Lambda\, \mathcal{L}_3$

$\mathcal{L}_2$: PROTECTED BY SUSY :

$$O(\Lambda^2)\mathcal{L}_2 \to \Delta M^2_{SUSY}\mathcal{L}_2$$

GUTS MAKE ν MASSES VERY PLAUSIBLE

- MOST GUT GROUPS REQUIRE EXISTENCE OF ν_R

(NOT SU(5), BUT SO(10), E6, ...)

$\bar{5}+10$ TOO NICE NOT TO BE IMPORTANT $\boxed{16 = \bar{5}+10+1}$!

- L NOT CONSERVED IN GUTS

ALSO:

- LARGE M_{GUT} OFFERS NATURAL MECHANISM FOR m_ν VERY SMALL

SEE-SAW MECHANISM

Yanagida
Gell-Mann, Ramond, Slansky

IN S.M. THERE IS NO LORENTZ INV., DIM ≤ 4 OPERATOR (COMPATIBLE WITH $SU(3) \times SU(2) \times U(1)$) THAT VIOLATES B AND/OR L

EXCEPT $M_{GUT} \, \nu_R^T \nu_R$ $\left(\bar{\nu}_R^c \nu_R = \nu_R^T C \nu_R \right)$

FOR EXAMPLE :

$$u + u \to e^+ + \bar{d}$$

IS OK (e.g. COLOUR : $3 + 3 = 6 + \bar{3}$)

BUT : $\frac{\lambda}{M^2} \bar{d}^c u \; \bar{e}^c u \Rightarrow$ DIM 6

$M \equiv M_{GUT}$ SU(5) $p \to e^+ \pi^0$

[SAME IN SUSY WITH R-PARITY CONSERV'N]

BUT IF ν_R IS INTRODUCED

THEN $\nu_R^T \nu_R$ IS $SU(3) \times SU(2) \times U(1)$ INVARIANT AND $\Delta L = 2$!

WITH ν_R L CONSERV. NOT AUTOMATIC!!

$$\mathcal{L}_\nu = \bar{L}\, h\, \nu_R\, H + h.c. +$$

$$\hookrightarrow m_D = h v \quad \text{(DIRAC)}$$

$$+ \nu_R^T M_R \nu_R +$$

$$+ \nu_L^T \frac{\lambda}{M_L} \nu_L H H$$

(MAJORANA)

$$\hookrightarrow m = \frac{\lambda v^2}{M_L}$$

$\boxed{\text{SEE-SAW MECHANISM:}}$

$$m = \begin{array}{c|cc} & & \\ \nu_L & \frac{\lambda v^2}{M_L} & m_D \\ \nu_R & m_D & M_R \\ & \nu_L & \nu_R \end{array}$$

$$|m_{light}| \simeq \frac{m_D^2}{M_R} \div \frac{\lambda v^2}{M_L}$$

$$m_{heavy} \simeq M_R$$

$$m^{eff} = \nu_L^T\, m_{light}\, \nu_L$$

IN GENERAL BOTH $O_5 \sim \nu_L^T \frac{\lambda^2}{M} \nu_L HH$

AND THE SEE-SAW MECHANISM

ARE OPERATIVE :

$$\nu_L^T m_\nu \nu_L = \nu_L^T m_D^T M^{-1} m_D \nu_L + \nu_L^T \frac{\lambda^2 v^2}{M} \nu_L$$

THE 2 TERMS HAVE THE SAME FORM, THE SAME TRANSF. PROPERTIES UNDER $\nu_L' = U \nu_L$, BUT DIFFERENT ORIGINS

[e.g. IN GUT'S m_D RELATED TO q & ℓ DIRAC MASSES]

THEY CAN BE OF COMPARABLE OR OF VERY DIFFENT SIZE

[e.g. $1/M_{GUT}$ VS $1/M_{P\ell}$]

ν MASSES AND COSMOLOGY

$$\rho_0 \equiv \Omega \rho_c = \Omega \frac{3H_0^2}{8\pi G} = \Omega h^2 \cdot 11 \frac{keV}{cm^3}$$

$H_0 = 100\,h$ km/s/Mpc

$\Omega = \Omega_m + \Omega_\Lambda = 1$ (FAVOURED BY INFLATION)

EXP : $\Omega_\Lambda \simeq 0.62 \pm 0.16 \pm ?$; $\Omega_m \simeq 0.24 \pm 0.10 \pm ?$

$\Omega \simeq 1 \pm 0.2 \pm ?$ $\qquad \Omega_m h^2 \simeq 0.12 \pm 0.05$

$h \simeq 0.7 \pm 0.2$

$\Omega_\nu \lesssim 0.3\,\Omega_m$ $\qquad \Omega_\nu h^2 \lesssim 0.04 \div 0.06$

AT DECOUPLING ($T \sim$ MeV) :

$$\frac{n_\nu}{n_\gamma} \cong \frac{3}{11}$$

(ν: LIGHT NEUTRINO WITH $m_\nu <$ MeV)

$n_\gamma \sim 400/cm^3 \Longrightarrow n_\nu \sim 110/cm^3$

$$\rho_\nu = n_\nu m_\nu = 110\, m_\nu/cm^3 = \Omega_\nu h^2\, 11 \frac{keV}{cm^3}$$

$$\boxed{\sum m_\nu \approx \Omega_\nu h^2\, 100\, eV \lesssim 6\, eV}$$

$m_\nu \sim 0.05\, eV \Longrightarrow \Omega_\nu \sim 10^{-3}$ $\quad [\Omega_{stars} \simeq 5 \cdot 10^{-3}]$

IMPRESSIVE EXP. RESULTS ON COSMOLOGICAL PARAMETERS

$H_0 \sim 0.6 - 0.7 \cdot 100\, km/Mpc\, s$

Hubble Telescope
(age of universe)

$\Omega_{TOT} \simeq \Omega_m + \Omega_\Lambda \simeq 1$ (INFLATION)

1st acoustic peak : Boomerang, Maxima

$\Omega_m \simeq \Omega_B + \Omega_{DM} \simeq 0.35$

LENSING

$\Omega_B \to 0.03$ Nucleosynthesis

$\Omega_{DM} \to \sim 0.3$ MASS DISTR'N AT LARGE SCALES

$\Omega_\Lambda \simeq 0.65$

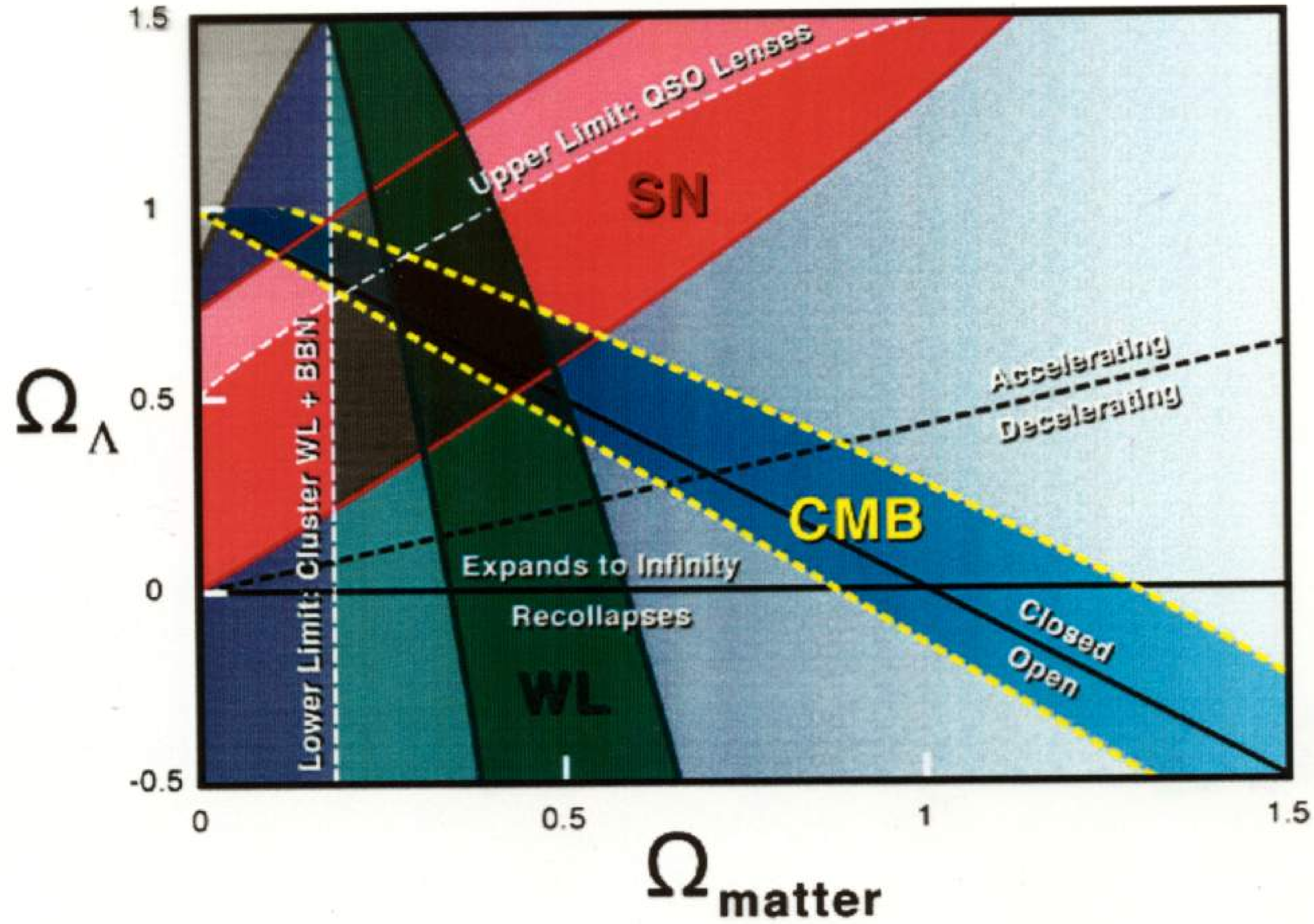
Supernovae
(age of universe)

WHY SO SMALL?
WHY NOW? (QUINTESSENCE)

$n = 1$

INHOMOGENEITY OF MASS DIST'N
FT $\rho \approx k^n$ (r LARGE)

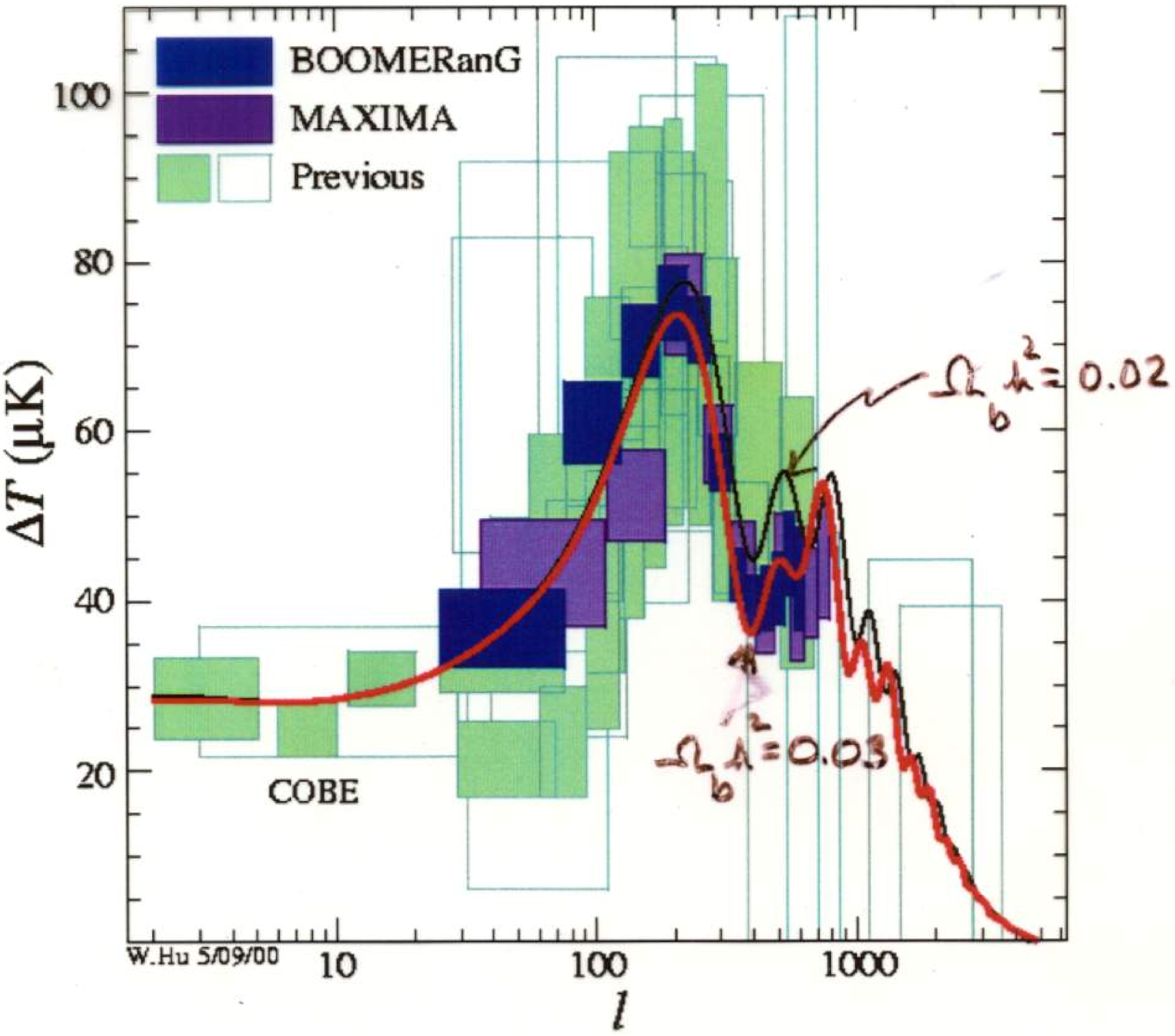
Status 2000



T. Tyson

Current Power Spectrum:

BOOMERanG and MAXIMA



Notes: black curve: LCDM Omega_m=0.35, h=0.65, Omega_b h^2=0.02, n=1; red curve: LCDM Omega_m=0.4, h=0.8, Omega_b h^2=0.03, n=1 n=1. Click on figure to download postscript version

BOOMERanG Nature Article: Nature 404, 955 (2000)

News and Views for the lay-scientist: Nature 404, 939 (2000)

FAQ on the BOOMERanG result

MAXIMA

Background Material

W.Hu

n: POWER-LAW INDEX OF DENSITY PERTURBATIONS

$n = 0.99 \pm 0.07$ (INFLATION $n \simeq 0.7 - 1.2$)

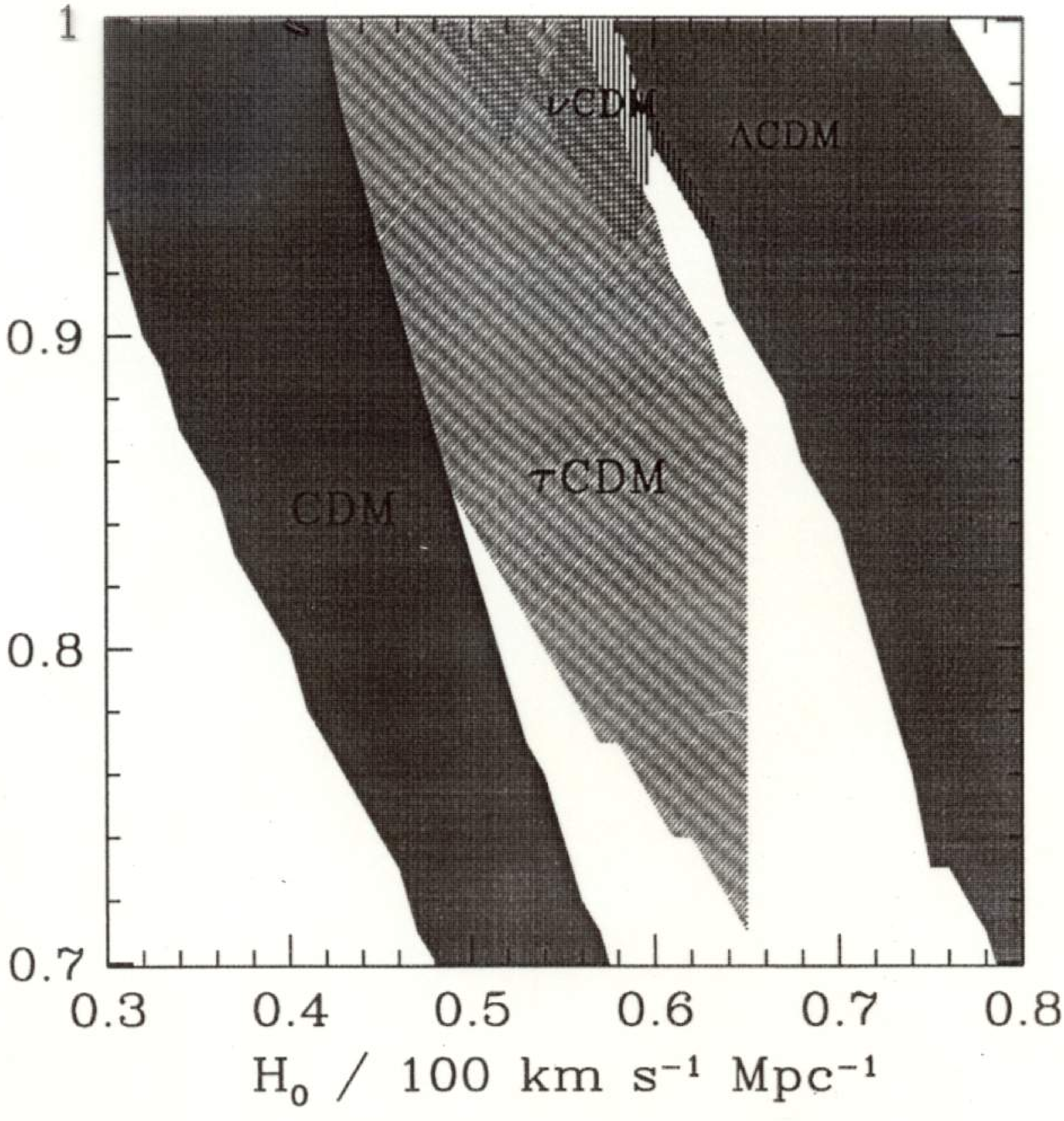


Figure 13: Acceptable cosmological parameters for different CDM models, as are characterized by their invisible matter content: simple CDM (CDM), CDM plus cosmological constant (ΛCDM), CDM plus some hot dark matter (νCDM), and CDM plus added relativistic particles (τCDM) (from Dodelson *et al.* , 1996).

VCDM HAS AN ISLAND OF VIABILITY AROUND $H_0 \sim 0.6$

$n \sim 0.95$

FOR $n \sim 1$ AND $H_0 > 0.6 \Rightarrow \Lambda$CDM

BARYOGENESIS $n_B/n_\gamma \sim 10^{-10}$, $n_{\bar{B}} << n_B$

Conditions for BG: (Sacharov '67)

- B non conserv'n ---> obvious
- C, CP non conserv'n--->B-$\bar{B}$ odd under C,CP
- No thermal equilibrium--->$n=\exp[(\mu-E)/kT]$

at equilibium $\mu_B = \mu_{\bar{B}}$

$m_B = m_{\bar{B}}$ by CPT

Warning: If different phases of BG exist at different scales the asymmetry created by one out-of-equilibrium phase at larger mass may be erased in subsequent equilibrium phases.

-----> BG at lowest scale best

M--> m_1, m_2....
(M heavy, B non cons. decay, out of eq.)--> BG
m-->μ_1, μ_2.... (B non cons. decay, in eq.)-- >
----> BG washed out

Possible epochs for BG

• BG at the EW scale T_{EW}~0.1-10 TeV

(Rubakov, Shaposhnikov; Cohen, Kaplan, Nelson; Quiros.....)

In SM:

•B non cons.by instantons 't Hooft

(negligible at T=0 but large at $T=T_{EW}$)

B-L conserved!!

•CP viol. by CKM phase

Enough?? By general consensus far too small

•Out of equilibrium during the EW phase transition

Needs strong 1st order phase trans. (bubbles):

Only possible for $m_H \leq 80$ GeV

NOW EXCLUDED BY LEP!

BG at the weak scale possible in MSSM?

- Additional sources of CP viol.

- Bounds on m_H modified by scalars with strong couplings to Higgs sector
(e.g s-top)

Requires:

$m_h \leq$ 80-100 GeV

$m_{s\text{-}top1} \leq m_t$

$\tan\beta \sim 1.2 - 5$ preferred

LEP HAS DECIDED: NO!

Espinosa, Quiros, Zwirner; Giudice; Myint; Carena, Quiros, Wagner, Laine; Cline, Kainulainen; Farrar, Losada..........

• BG at the GUT scale

$T \sim 10^{12}$-10^{15} GeV (after inflation)

Only survives if $\Delta(B-L) \neq 0$
(otherwise is washed out at $\geq T_{EW}$ by instantons).

A most attractive possibility:

BG via leptogenesis

ν_R are heavy: $M \sim 10^{12}$-10^{15} GeV

L viol. in ν_R out-of-equilibrium decay:
B-L excess is created that at T_{EW} survives and produces B viol.

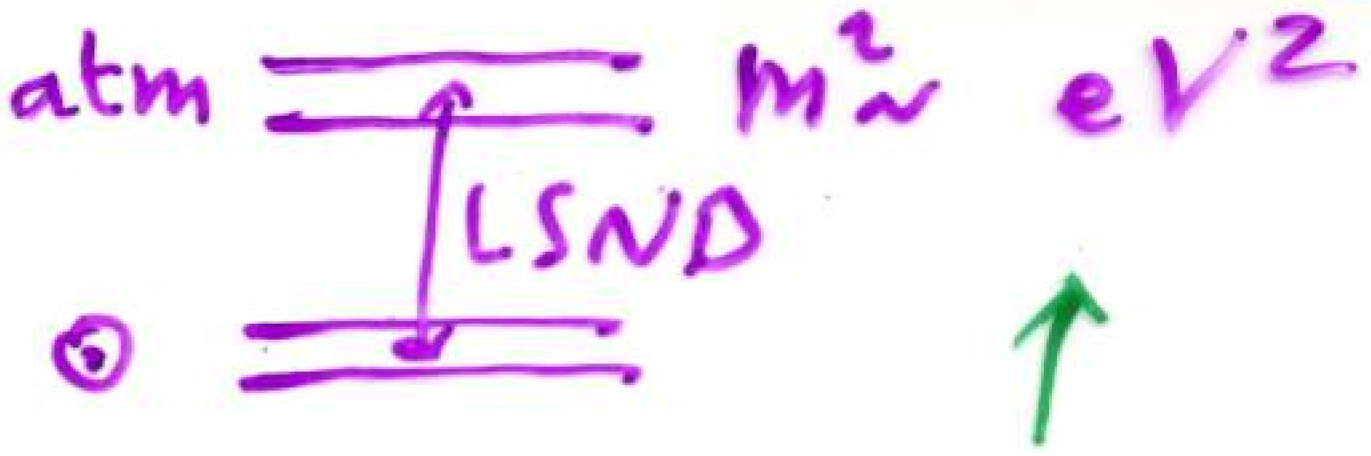
Quantitative studies show that for $m_3 >> m_{1,2}$, the range of $m_{1,2}$ from ν oscillations is compatible with BG via LG

$$10^{-6} \leq m_{1,2} \leq 10^{-2} \text{ eV}$$

(Buchmuller, Yanagida; Plumacher; Ellis, Lola, Nanopoulos; Giudice et al……)

THERE ARE MANY ALTERNATIVE MODELS

- $\boxed{\gtrsim 4\,\nu's}$ (LSND)



$\nu_{STERILE}$??

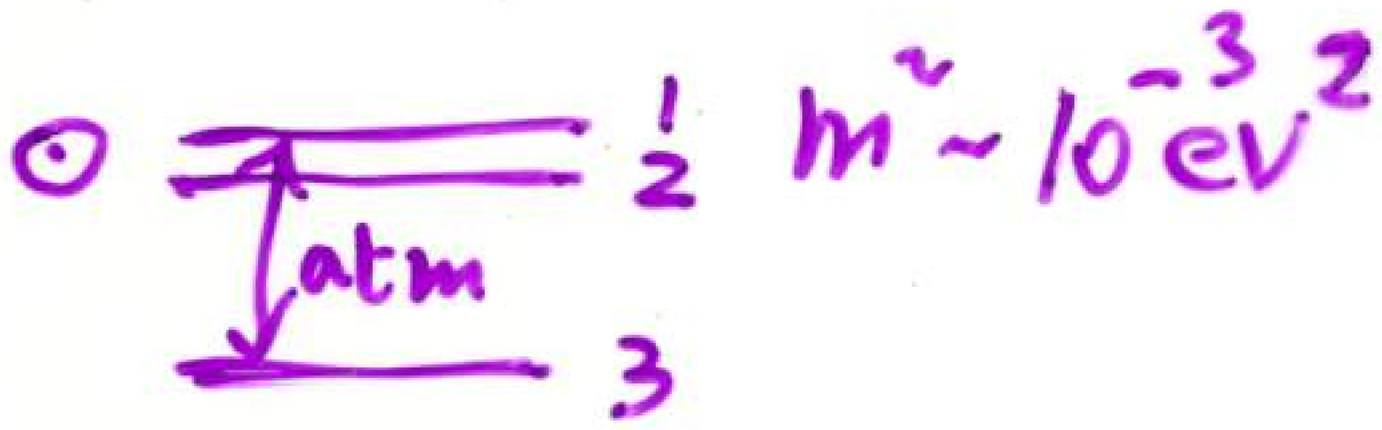
HOT DARK MATTER

$\boxed{3\,\nu's}$ (NO LSND)

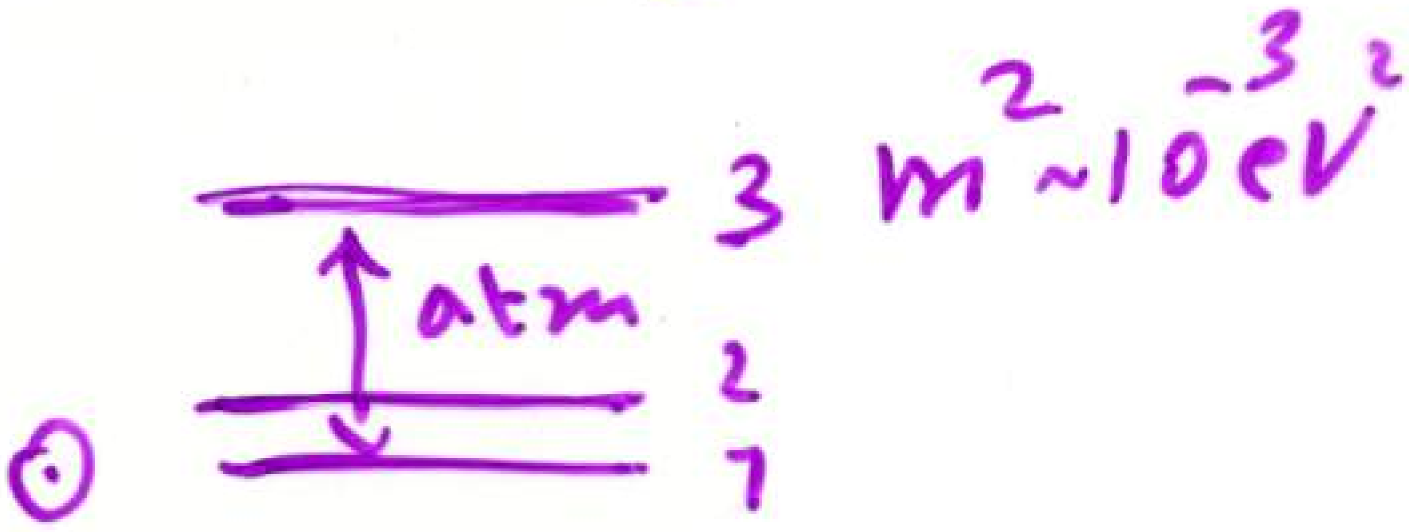
- DEGENERATE

$0\nu\beta\beta$ CLOSE TO LIMIT

- INVERSE HIERARCHY



- NORMAL HIERARCHY



I WILL ARGUE FOR THIS CASE

$m_\nu \sim m^T_{Dirac}\, M^{-1}\, m_{Dirac}$ DOMINANCE OF SEE-SAW + GUT's

CONNECTION TO q, ℓ MASSES VIA GUT'S

MODELS AND IDEAS

- $SU(5) \otimes U(1)_{HORIZONTAL}$ MODELS
- FROM MINIMAL TO "REALISTIC" SU(5)
- SU(5) FROM EXTRA-DIMENSIONS

ν_R is a heavy "sterile" neutrino:

sterile: no gauge int's

ν_R has: colour = t_3^W = Q = 0

ν_L is a light "active" neutrino:

LEP: $N_{\nu L} = 3$

Are there light sterile neutrinos?

----> Is LSND signal true?

LSND + Solar + Atm. Oscill's

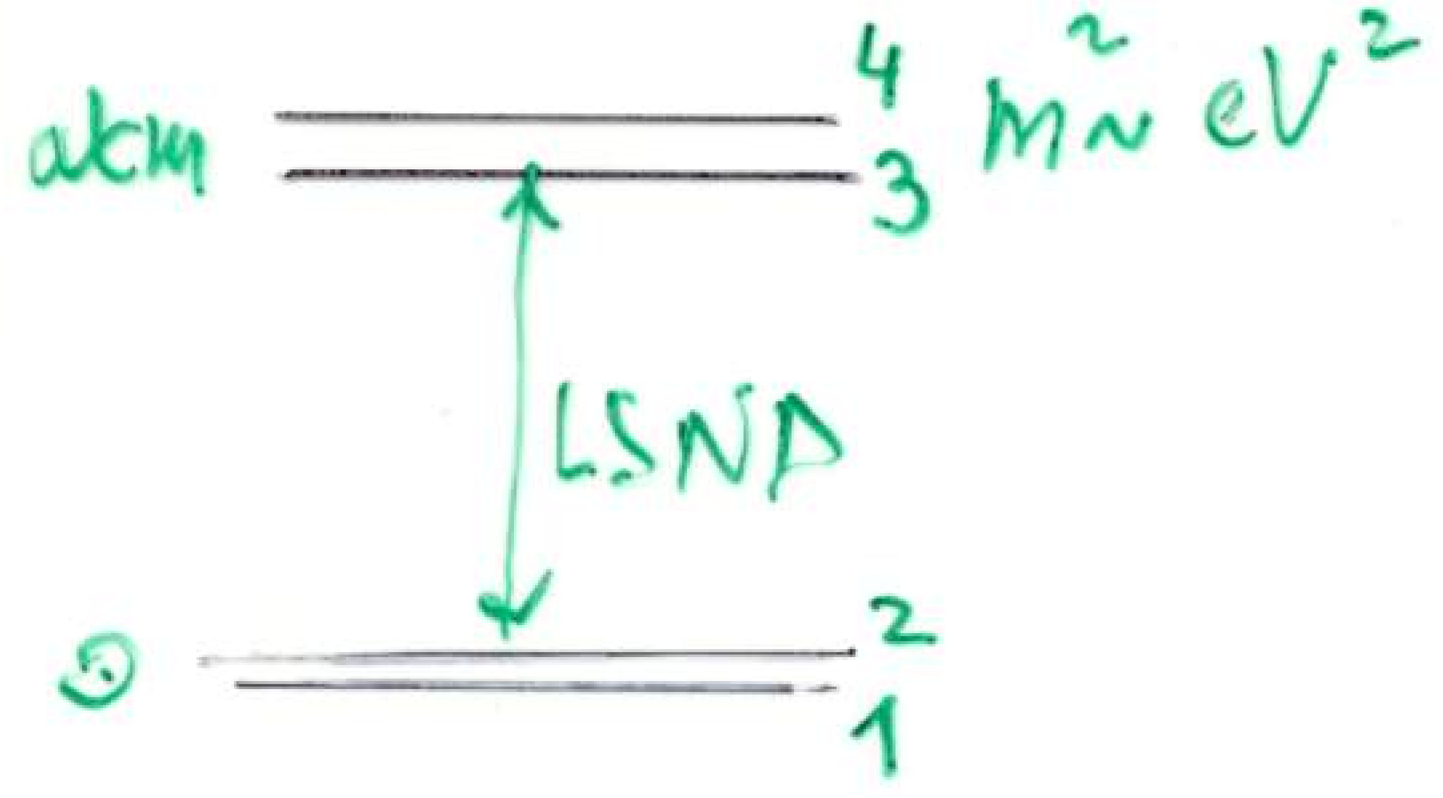
----> at least 4 light ν's

LSND not double checked (MiniBoone)
KARMEN did not confirm

Perhaps will fade away. But if right
LNSD + Solar + Atm -----> ≥ 4 ν's
or ≥ 1 light sterile ν's

4-ν Models

Typical configuration (Bilenky et al; Barger et al; Gonzales-Garcia et al)



•Can be compatible with hot dark matter, $m_{4,3}$~2 eV

• Pure two-neutrino ν_e<-->ν_s oscill's disfavoured for solar

Viable alternatives:

• 6->4 mixing angles: ν_e <--> $\nu_s + \nu_a$ (a: active=μ,τ) for solar Gonzales-Garcia et al; Fogli, Lisi

• A K-K tower of sterile ν_s (extra-dim models)

Since ν_s mixings better be small (limits from weak processes, supernovae, nucleosynthesis) the preferred solar neutrino solution is MSW-SA

Sterile ν's from extra dimensions

Context:
Large extra dimensions
Gravity propagates in all dim (bulk)
SM particles on a 4-dim brane

$$d = n + 4$$
$$(m_s R)^n = (M_P/m_s)^2$$
$$m_s \sim \text{TeV}$$

Assume 1 very large dim: $1/R \leq 0.01$ eV
+ n-1 smaller ($1/\rho \geq$ TeV)

$$(m_s R)\,(m_s \rho)^{n-1} = (M_P/m_s)^2$$
or
$$(m_5 R) = (M_P/m_s)^2$$

ν_s: SUSY partners of gravitational moduli (string th.)
Also propagate in the bulk

(Arani-Hamed et al; Benakli and Smirnov, Dvali and Smirnov, Faraggi and Pospelov, Mohapatra et al, Ioannisian and Pilaftis, Ioannisian and Valle, Barbieri et al. Lukas et al; Dienes and Sarcevic, Caldwell et al;

Good Features

Caldwell et al, Mohapatra et al, Lukas et al

- A "physical" picture for ν_s.

- ν_s has KK recurrences:

$$\nu_s(x,y) = 1/\sqrt{R} \sum_n \nu_s^{(n)}(x) \cos(ny/R)$$

with: $m_{\nu s} = n/R$

and mixes with L:

$$h(m_s/M_P)\, L\nu_s^{(n)}\, H$$

[the suppression factor (m_s/M_P) is automatic from the bulk volume!]

- Interference among a few KK states make spectrum compatible with solar data

$$P(\nu_e\text{->}X) = \sum_n m^2_e/(M^2_e + n^2/R^2)$$

$1/R \sim 10^{-2} - 10^{-3}$ eV

$R \sim 10^{-3} - 10^{-2}$ cm: very close to limits!!

Problems

- GUT's? Connection with GUT's?
- What forbids (on the brane)

$$1/m_s \, L^T \lambda L H H \quad ??$$

Recall that m_s is small ~ TeV

- ν_e, ν_μ, ν_τ ??
- Only 1 large extra dim has problems

(linear evolution of couplings from 0.01 eV to TeV) Antoniadis, Bachas; Arkani Hamed et al

But more large extra dim

$$P(\nu_e\text{->}X) = \sum_n m^2_e/(M^2_e + n^2/R^2)$$
$$= \int m^2_e \, n^{d-1} \, dn \,/(M^2_e + n^2/R^2)$$

High KK states do not decouple fast enough, mixing large.

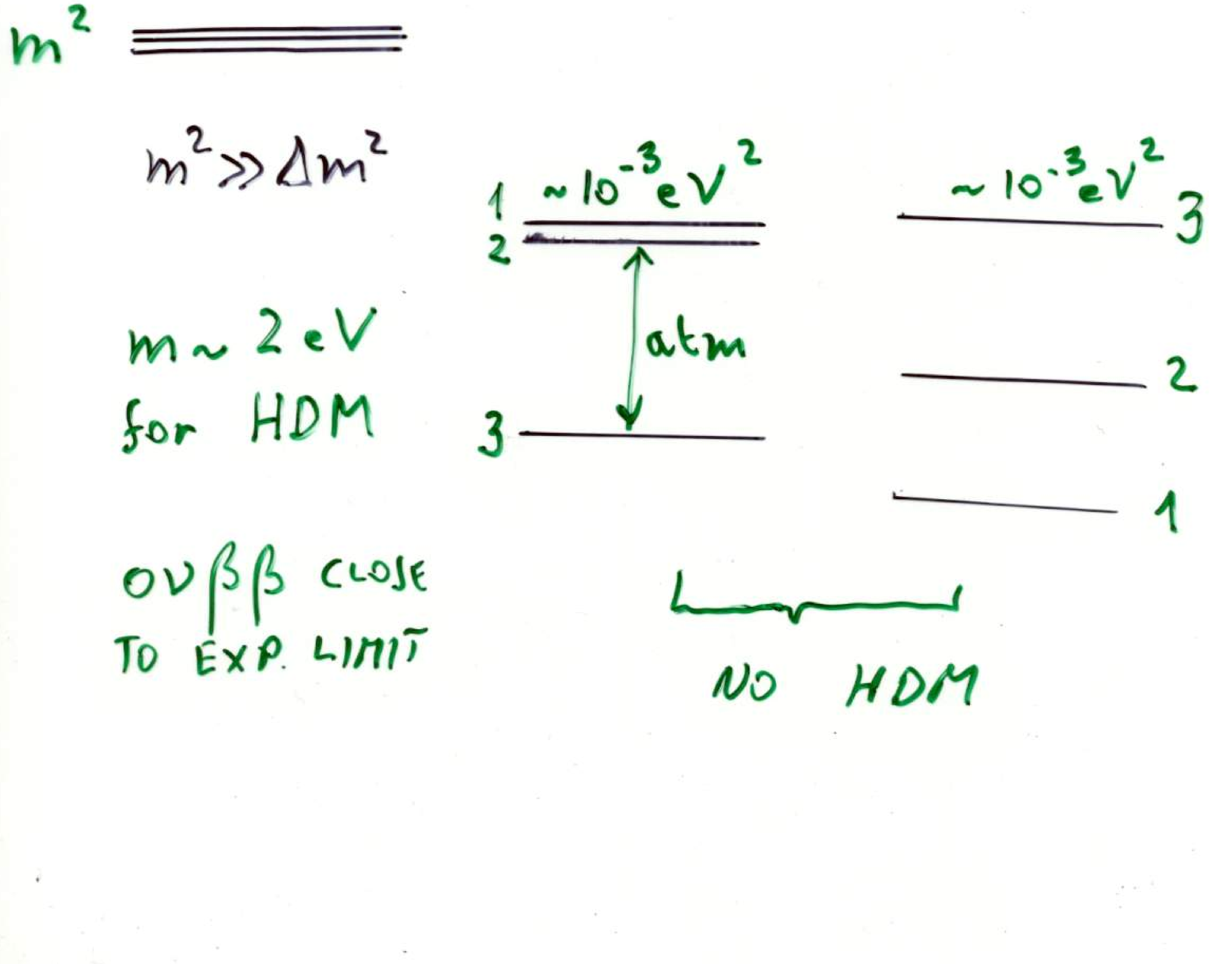
Compromise d=2?

3-ν Models

$\Delta m^2_{atm} = m_3^2 - m_{1,2}^2 \sim 2.5\ 10^{-3}\ eV^2$
$\Delta m^2_{sun} = m_2^2 - m_1^2 << \Delta m^2_{atm}$

Possible configurations

Degenerate Inverted Hierarchical



Degenerate ν 's

- Compatible with hot dark matter ($m \sim 2$ eV)

- Limits on m_{ee} from $0\nu\beta\beta$ imply double maximal mixing (bimixing) for atmospheric and solar oscill's:

Vissani; Georgi, Glashow.

$$m_{ee} = m_1 \cos^2\theta_{12} + m_2 \sin^2\theta_{12}$$

$m_{ee} \leq 0.3\text{-}0.5$ eV (exp.) needs

$$m_1 = - m_2$$

and

$$\cos^2\theta_{12} \sim \sin^2\theta_{12}$$

[Note: $\sin^2 2\theta > 0.99$ ---->$\cos^2\theta - \sin^2\theta < 0.1$]

$0\nu\beta\beta$ near the bound would be a signal!!

- For naturalness $\Delta m/m$ cannot be too small (e.g. vacuum sol. $\Delta m/m \sim 10^{-11}$) MSW-LA would be preferred in this respect. But is θ_{12} sufficiently maximal?

•For degenerate ν's see-saw dominance is unlikely:

See-saw: $m_\nu = m^T{}_D M^{-1} m_D$

We expect m_D to be hierarchical as for q & l

(conspiracy between m_D and M unplausible)

More likely:

Degenerate ν's from dim-5 operators

$$1/M \ \ L^T \lambda L \ H \ H$$

unrelated to m_D and q & l.

•For m ~ 2 eV, v ~ 200 GeV, λ ~ 1:

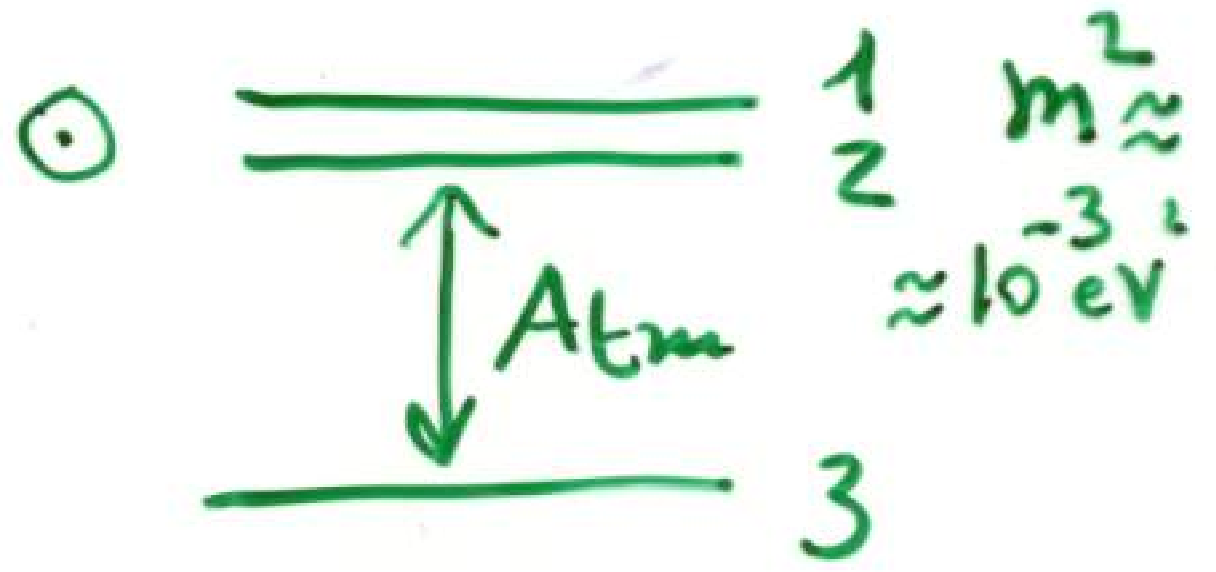
$M \sim 10^{13}$ GeV Somewhat low?

Inverted hierachy

Joshipura et al; Mohapatra et al; Jarlskog et al; Frampton and Glashow; Barbieri et al.........; Zee

Provides interesting models for bimixing.

$$U = \begin{bmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/2 & 1/2 & -1/\sqrt{2} \\ 1/2 & 1/2 & 1/\sqrt{2} \end{bmatrix}$$



$$m_{diag} = M \begin{bmatrix} 1 & & \\ & -1 & \\ & & 0 \end{bmatrix}$$

$$U\, m_{diag}\, U^{+} = 1/\sqrt{2} \begin{bmatrix} 0 & M & M \\ M & 0 & 0 \\ M & 0 & 0 \end{bmatrix} \text{(in flavour basis)}$$

- From dim-5 $L^T LHH$
- Approximate L_e-L_μ-L_τ symmetry.
- 1-2 degeneracy stable under rad. correct's.
- Prefers VO or LOW for solar, but could be comp. with MSW-LA

(is mixing large enough?)

SIGN OF Δm^2_{32} : (MATTER EFFECTS)

LONG BASELINE EXP'S
[ν FACTORIES]

S. Geer

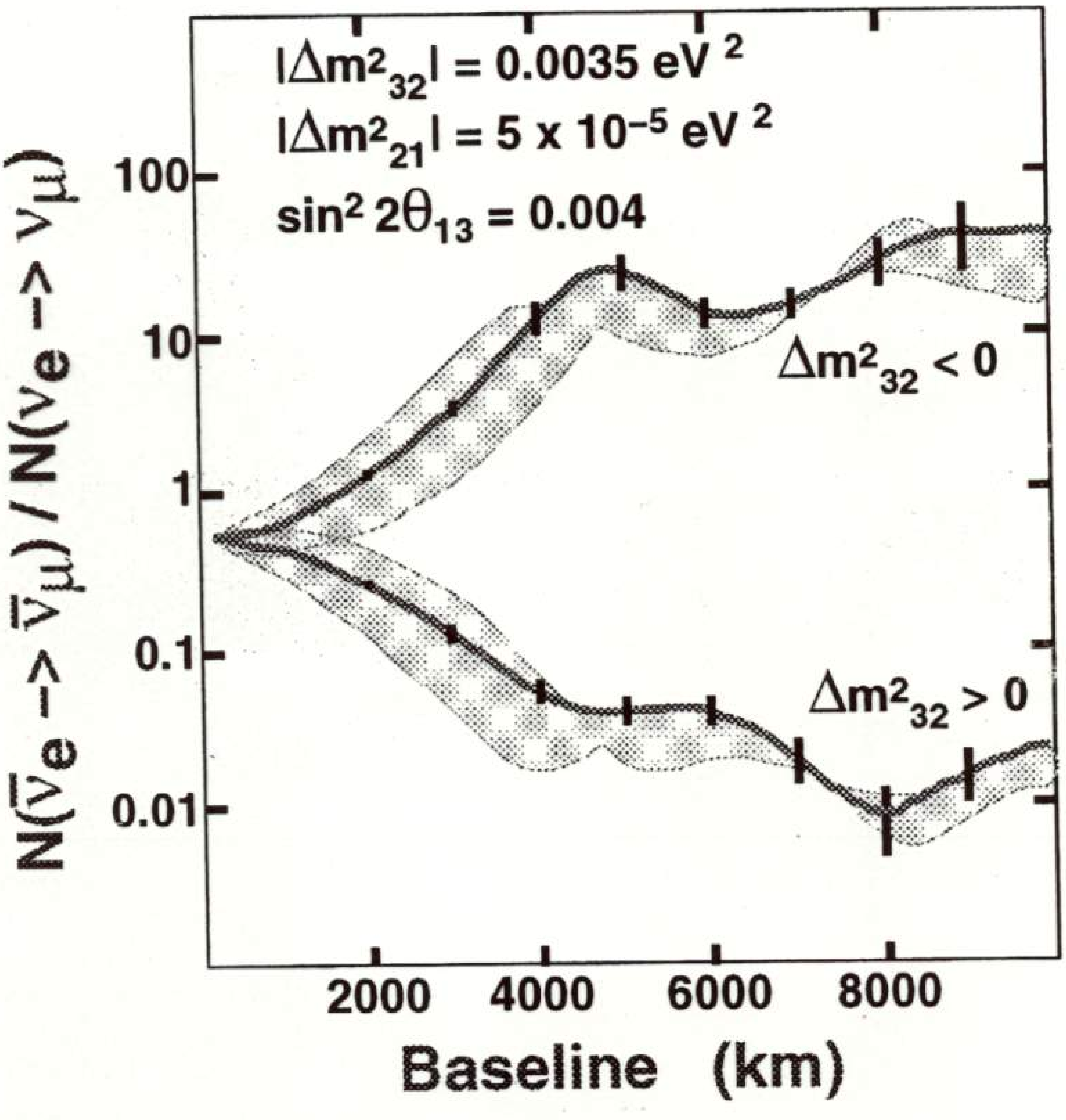
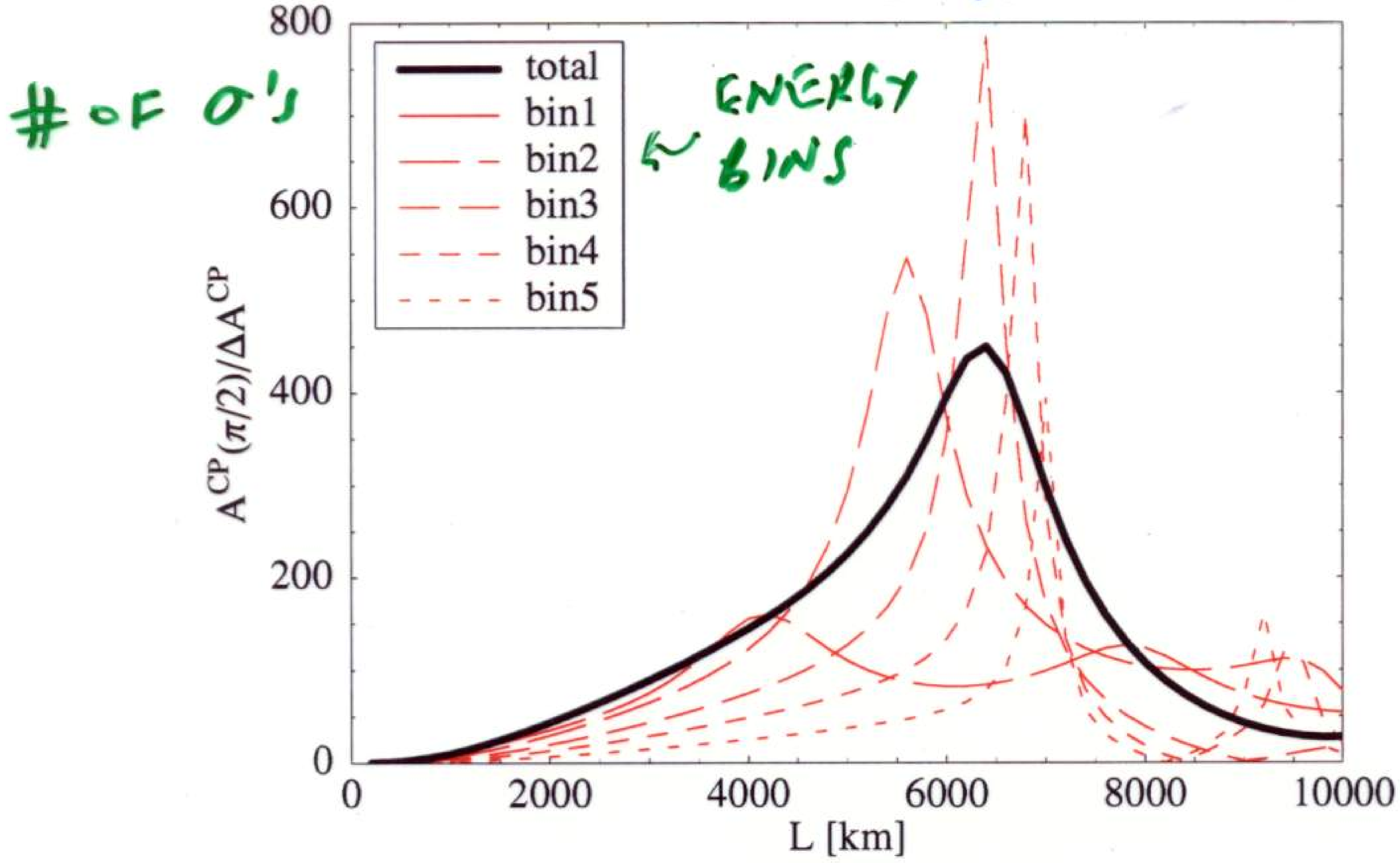


Figure 6: Measuring δ and sign(Δm^2_{32}) at a Neutrino Factory. In this plot the bands correspond to varying δ between 0 and $\pi/2$, and the error bars are estimated for a high performance Neutrino Factory (taken from ref.[20].)

MSW - SA

P. Hernandez et al



FAKE CP ASYMMETRY INDUCED BY MATTER

EFFECTS

THE SENSITIVITY TO $\mathrm{sign}[\Delta m^2_{23}]$ IS DIRECTLY THIS ONE

Hierarchical neutrinos

- Assume 3 widely split light neutrinos
- SO(10)--->ν_R + assume see-saw dominant:

$$m_\nu \sim m_D^T M^{-1} m_D$$

Maximally constraining: Gut's relate q, l, ν masses!!

- For u, d, l Dirac mass matrices: the 3[rd] generation eigenv. dominant.
- It is natural to assume this is also true for m_D^ν: diag $m_D^\nu \sim (0,0,m_{D3})$
- After see-saw, $m_\nu \sim m_D^T M^{-1} m_D$, in general will be even more hierarchical: fine tuned compensation between m_D and M unlikely.

•A possible problem:

We need both large m_3-m_2 splitting and large mixing in 2-3 sector.

$$m_3 \sim (\Delta m^2_{atm})^{1/2} \sim 5\ 10^{-2}\ eV$$
$$m_2 \sim (\Delta m^2_{sol})^{1/2} \sim \ 2\ 10^{-3}\ eV\ -\ 10^{-5}\ eV$$
$$\text{(MSW)} \qquad\qquad \text{(VO)}$$

•The "theorem" that large Δm_{32} implies small mixing (pert. th.: θ_{ij}~$1/|E_i-E_j|$) is not true in general:
All we need is (sub)det[23]~0

NOTE: for MSW-LA the splitting could be by a factor of ~10 only: a factor of 3 in m_D easily becomes a factor of 10 in

$$m_\nu \sim m_D^T M^{-1} m_D$$

Example

$$m_{23} \sim \begin{bmatrix} x^2 & x \\ x & 1 \end{bmatrix}$$

$\mathrm{Det}[m_{23}] \sim 0$

Eigenvalues: $0,\ 1+x^2$

Mixing: $\sin^2(2\theta) = 4x^2/(1+x^2)^2$

For $x \sim 1$ large splitting and large mixing!

So we need mechanisms for $\mathrm{Det}[m_{23}] \sim 0$ automatic.

MECHANISMS FOR $\mathrm{Det}[23] \sim 0$

$$\boxed{m_\nu = m^T M^{-1} m}$$

(1) A ν_R IS LIGHTEST AND COUPLED TO μ & τ : King, Allanach, Barbieri et al

$$M \sim \begin{pmatrix} \epsilon & \\ & 1 \end{pmatrix} \to M^{-1} \sim \begin{pmatrix} 1/\epsilon & \\ & 1 \end{pmatrix} \simeq \begin{pmatrix} 1/\epsilon & \\ & 0 \end{pmatrix}$$

$$m_\nu \sim \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 1/\epsilon & \\ & 0 \end{pmatrix} \begin{pmatrix} a & c \\ b & d \end{pmatrix} \approx \frac{1}{\epsilon} \begin{pmatrix} a^2 & ac \\ ac & c^2 \end{pmatrix}$$

(2) M GENERIC, BUT $m \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & x & 1 \end{pmatrix}$

$$M^{-1} \sim \begin{pmatrix} a & b & c \\ b & d & e \\ c & e & f \end{pmatrix}$$

$$m_\nu \approx f \begin{pmatrix} 0 & 0 & 0 \\ 0 & x^2 & x \\ 0 & x & 1 \end{pmatrix}$$

G.A, F. Feruglio

• Hierarchical neutrinos and see-saw dominance

$$m_\nu \sim m_D{}^T M^{-1} m_D$$

allow to relate q, l, ν masses and mixings**-->**
--> GUT's models

•The correct pattern of masses and mixings, also including ν's, is obtained in simple models based on

$$SU(5) \otimes U(1)_{horizontal}$$

•SO(10) models are often more predictive, but are based on specific textures from a set of special operators
(Albright, Barr; Babu et al; Buccella et al ......)

SIMPLEST FN ($\Rightarrow$ RARONSO)
PREDICTS

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$$

$\hookrightarrow \det m_{23} \neq 0 \; (O(1))$

OR $\quad m_2 \sim m_3$

$\theta_\odot$ SMALL

THUS SMA IS NO GOOD

$$\frac{m_3}{m_2} \sim 20\text{-}30 \sim \frac{1}{\lambda^2}$$

AND LA SOLUTIONS ARE NO GOOD EITHER ($\theta_\odot$ LARGE)

BUT ONE CAN DO MODELS THAT WORK ($\det m_{23} \sim \lambda^n$, $\theta_\odot$ SMALL OR LARGE
(NEGATIVE CHARGES, MORE FLAVONS...)

The Far Future: ν Factories

- An intense beam of muons, 10^{21} μ^+, E_μ~50 GeV.
- Long baseline ~750-3000-7000 Km.
- Magnetized iron detector of ~40 Kton.

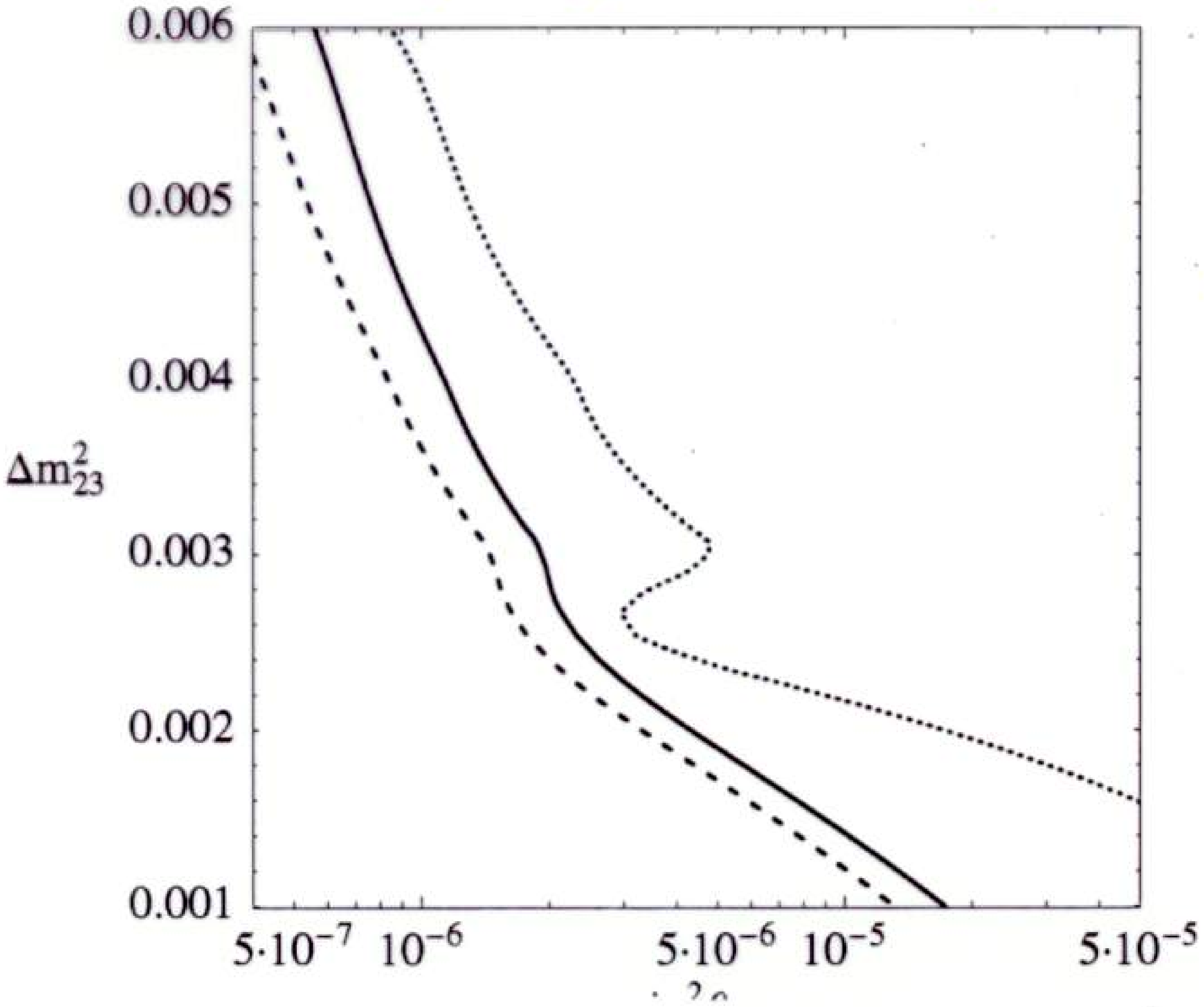
$\mu^+ \text{---->} e^+ \nu_e \bar{\nu}_\mu$:
If ν_e oscillates into ν_μ produces "wrong sign" muons.

At the time of the ν factory Δm^2_{23} and $tg^2\theta_{23}$ will be known precisely, not θ_{13}, δ and sign[Δm^2_{23}].

θ_{13}, δ and sign[Δm^2_{23}] are goals of ν factories.

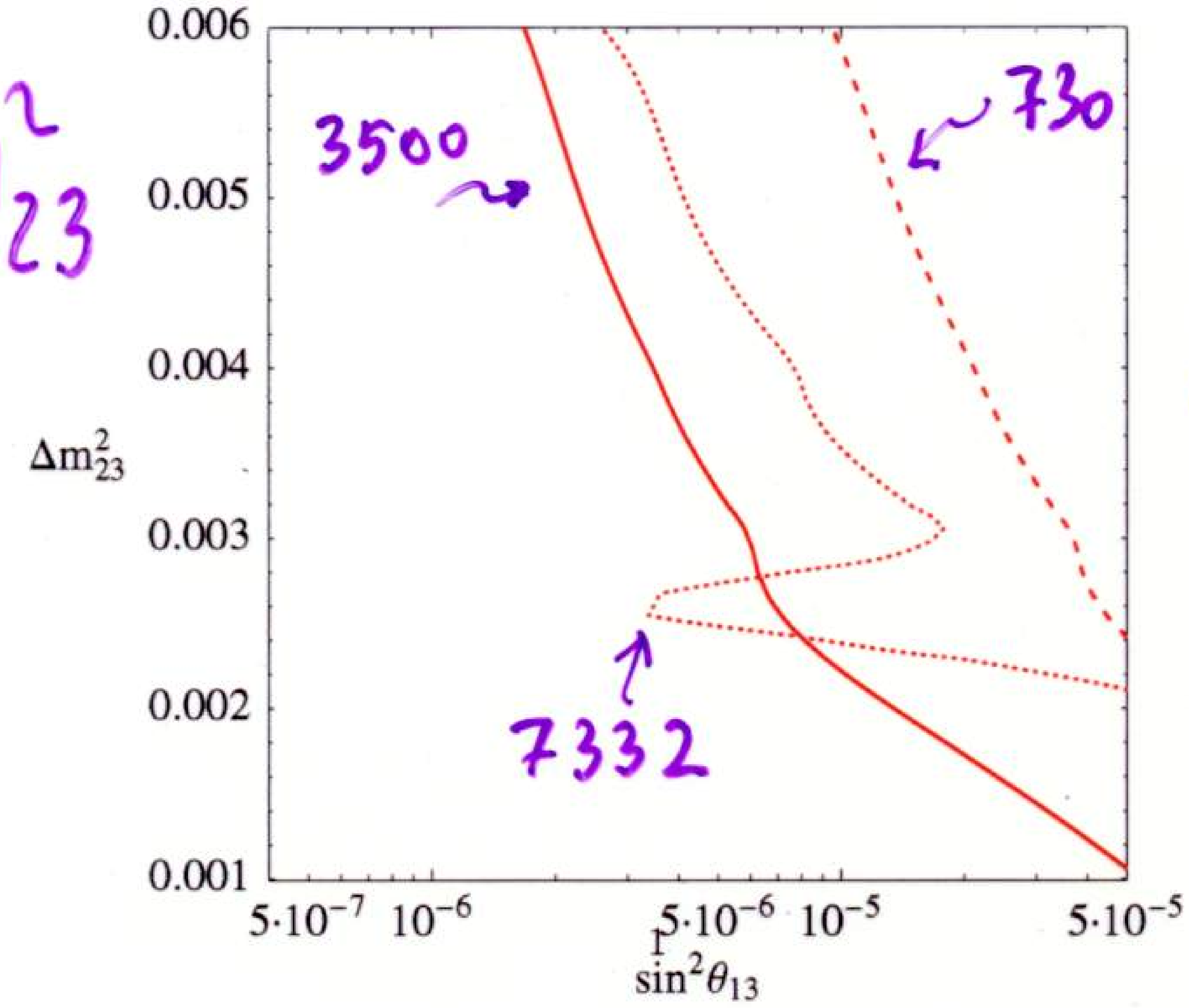
EXCLUSION PLOTS

P. Hernandez et al



ONLY STATISTICAL ERRORS

Δm^2_{23}



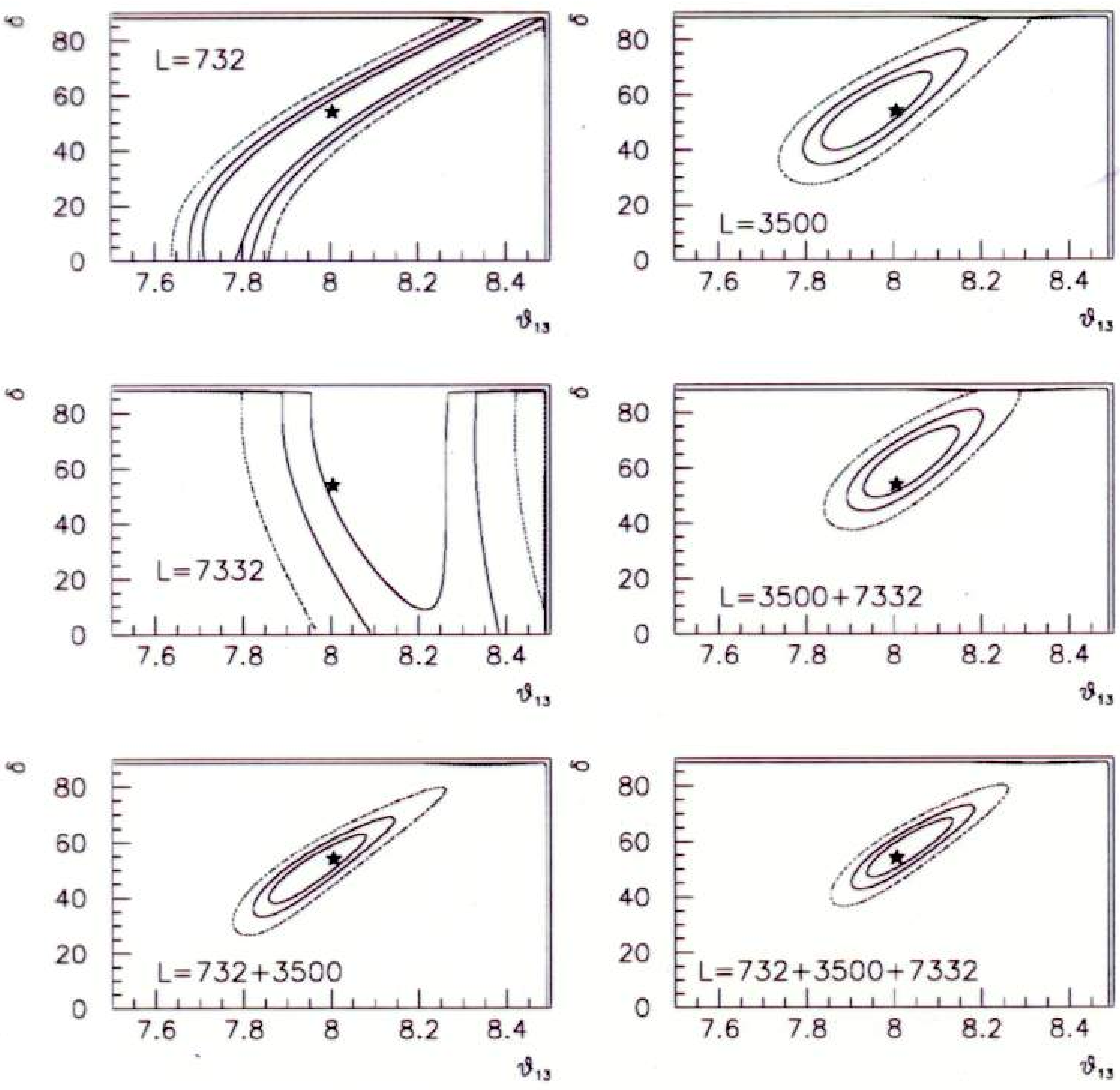
ALL ERRORS INCL.

$\sin^2\theta_{13}$

FITS TO θ_{13} AND δ

~~CP~~ DETECTION REQUIRES LA

δ



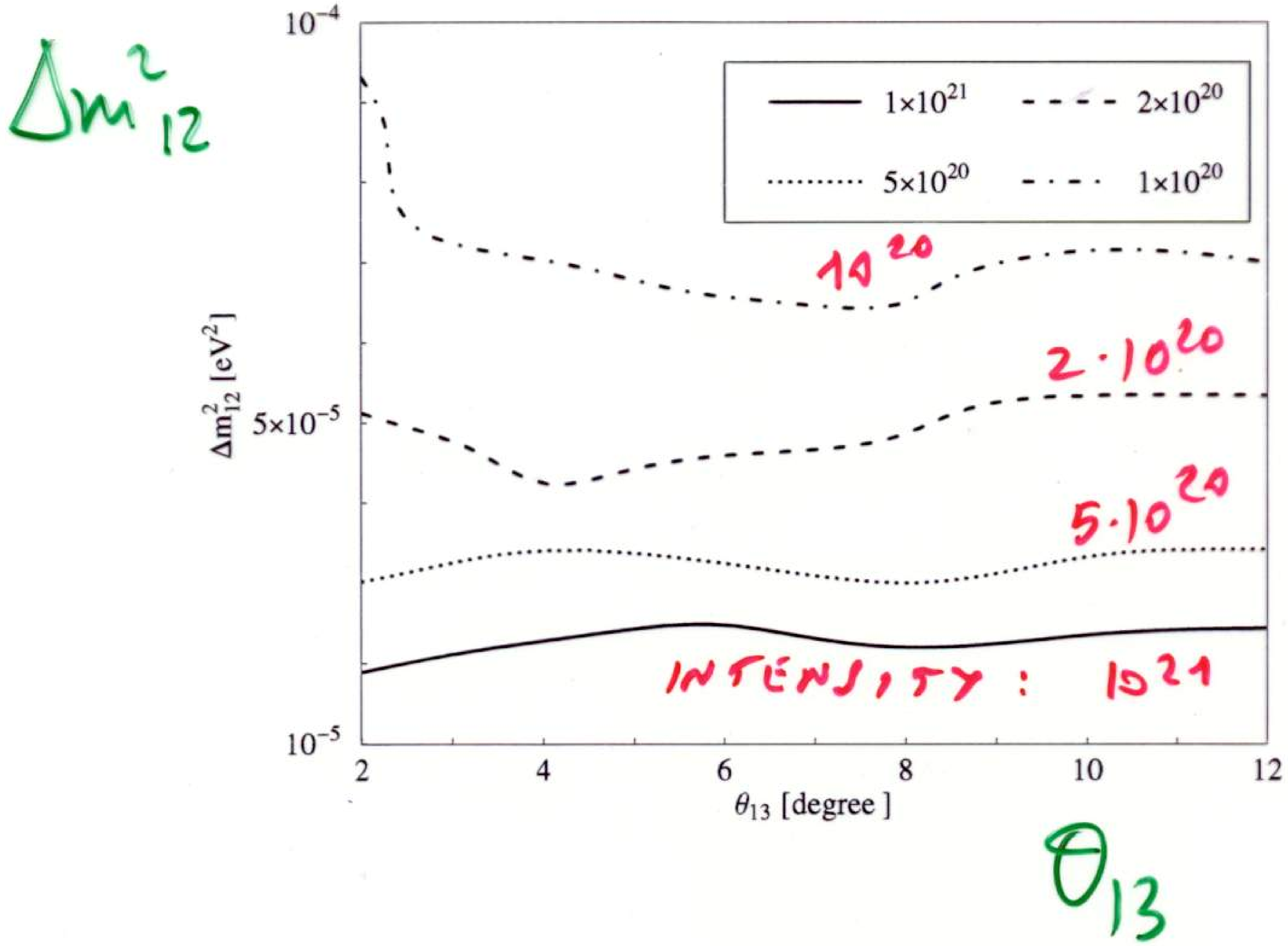
θ_{13}

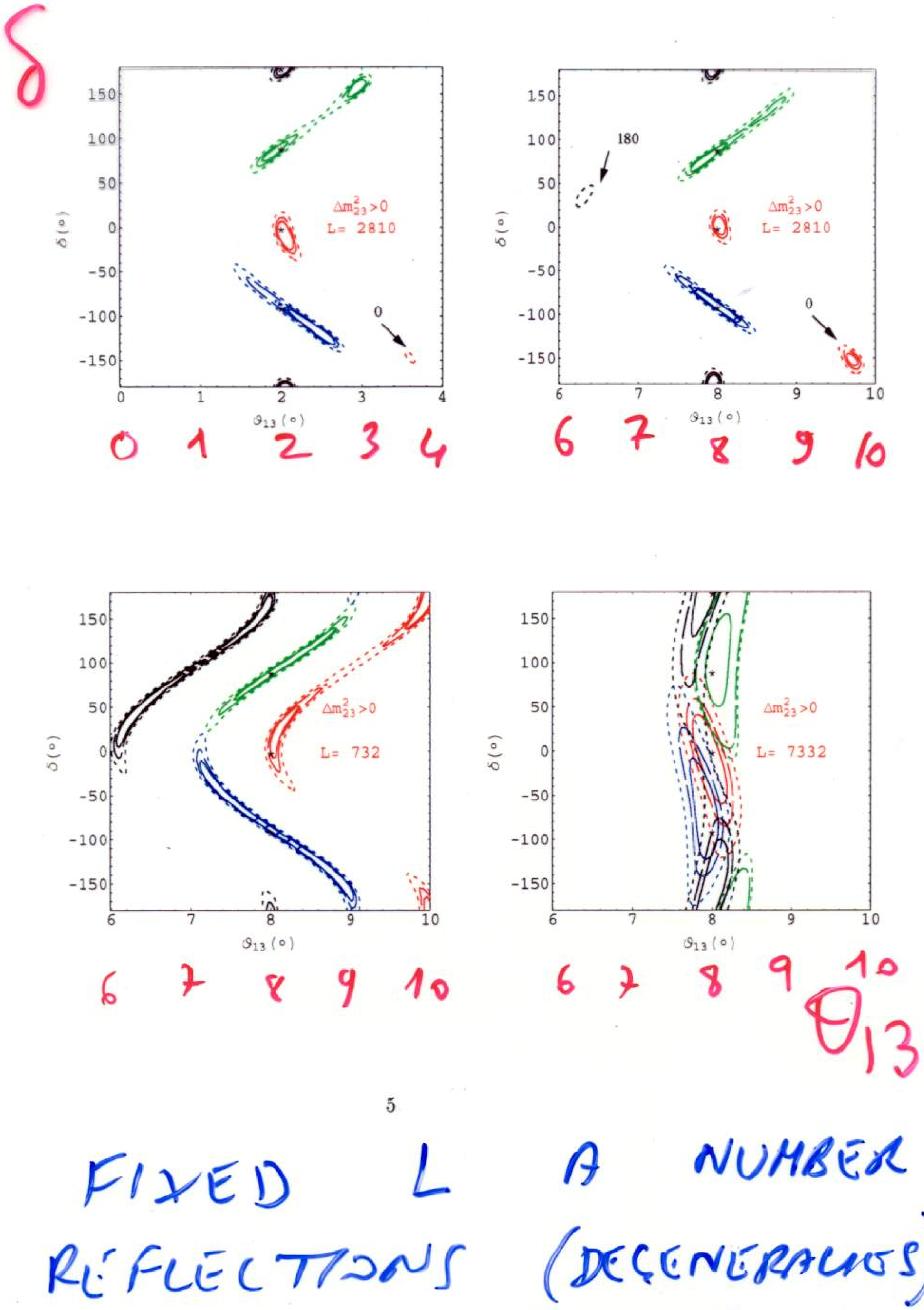
ASSUMED CENTRAL VALUES

$\theta_{13} = 8°$

$\delta = 54°$

MINIMUM Δm^2_{12} AT WHICH $\delta = 0$ AND $\delta = \frac{\pi}{2}$ CAN BE DISTINGUISHED

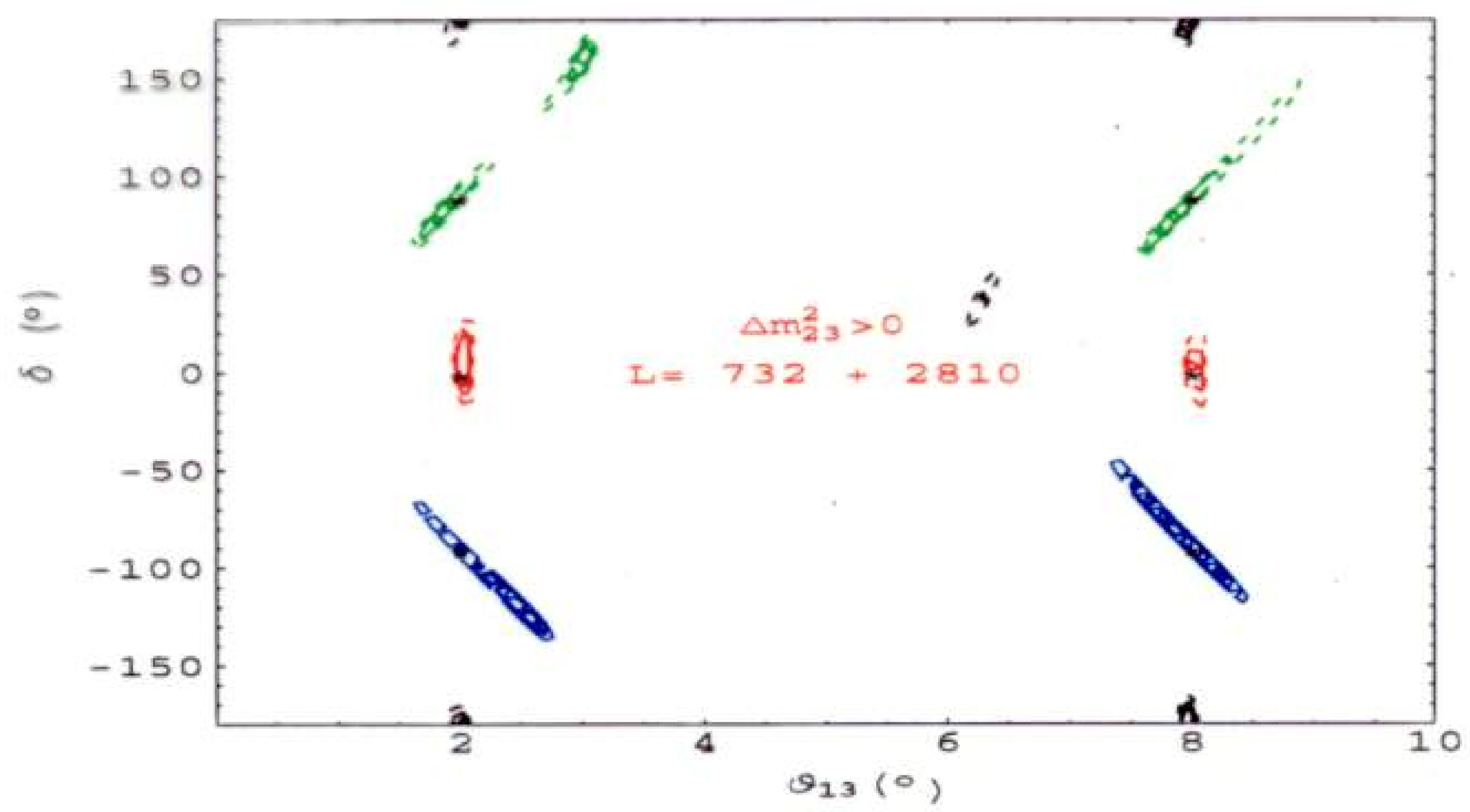


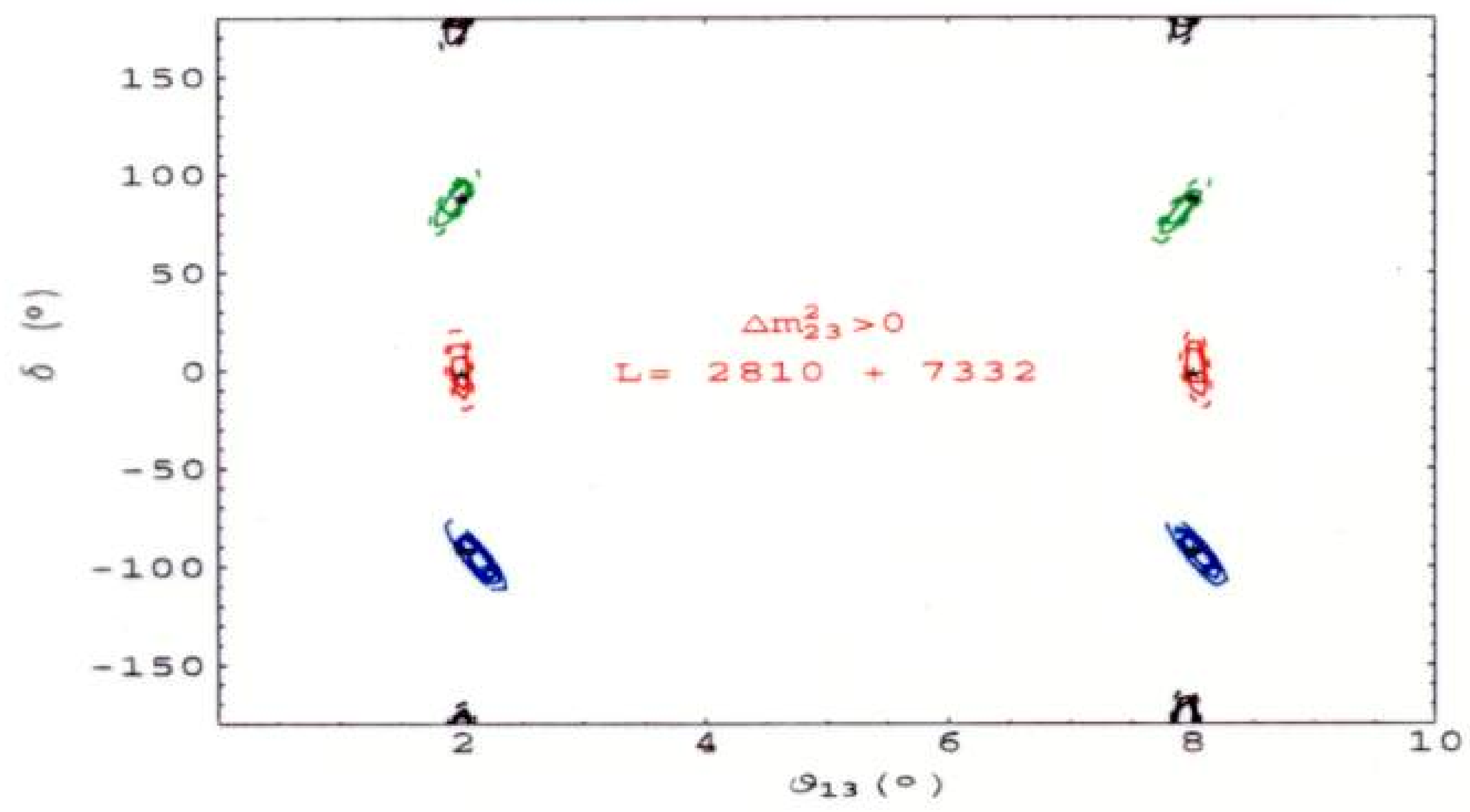


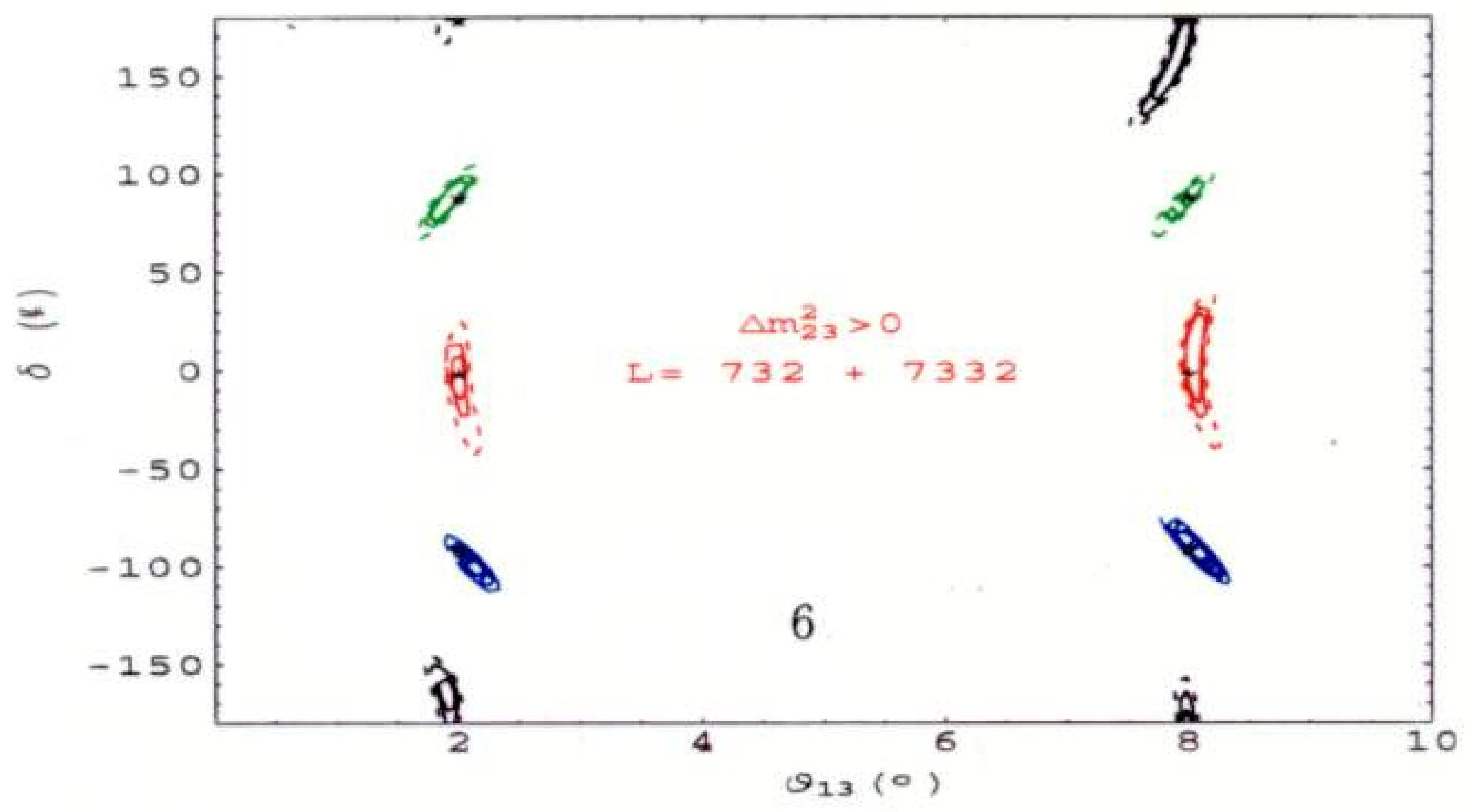
AT FIXED L A NUMBER OF REFLECTIONS (DEGENERACIES) ARE PRESENT

$\delta \leftrightarrow \pi-\delta$

$\theta_{13} \leftrightarrow \theta_{13}+\Delta$

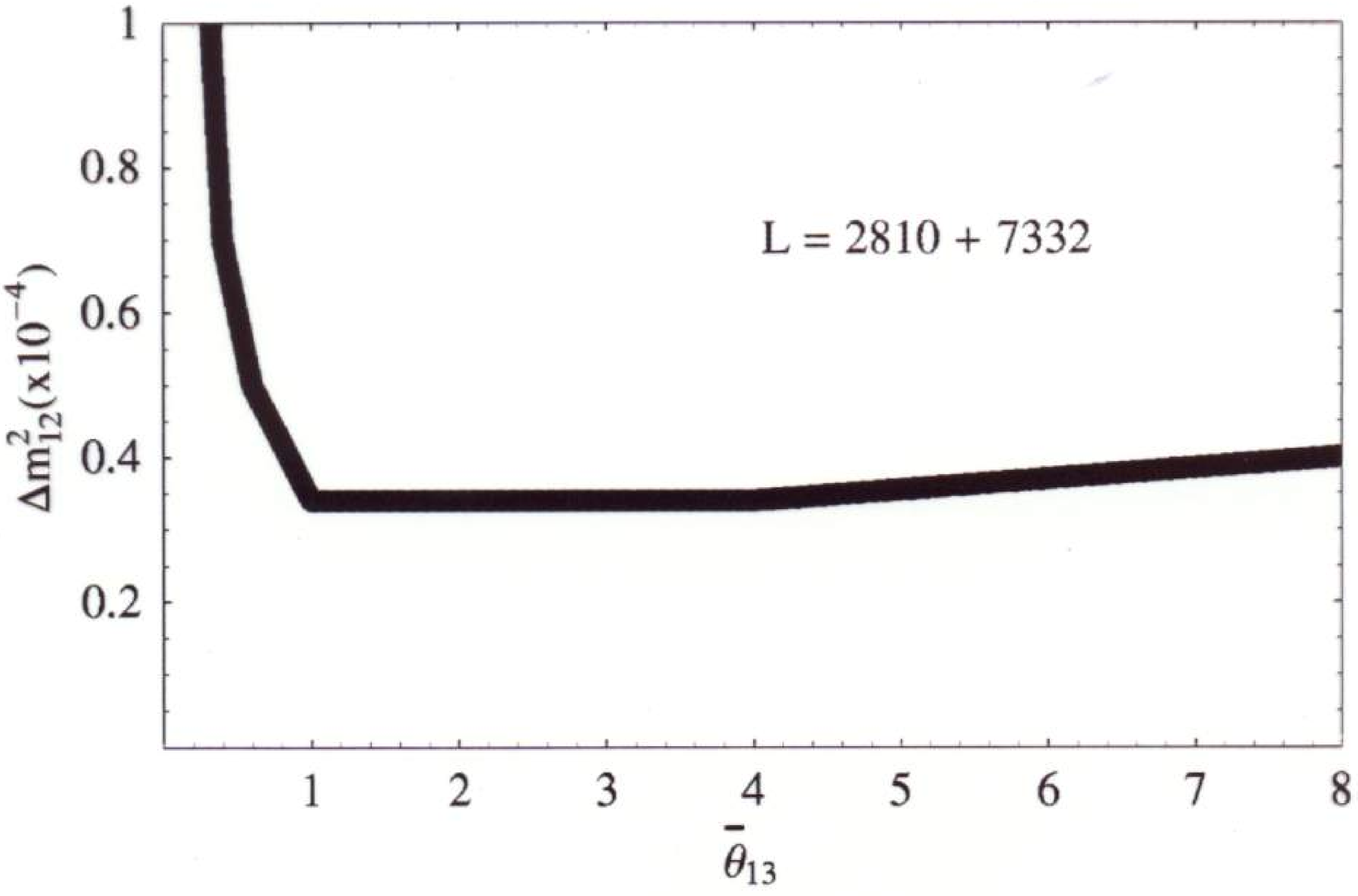






REFLECTIONS ARE ELIMINATED BY COMBINING DIFFERENT L'S

LINE AT WHICH $\delta = 90°$ IS DISTINGUISHED FROM 0° OR 180° AT 99% C.L.



Conclusion

• Many crucial questions to be answered by experiments, e.g.

LNSD: true or false
Which solar ν solution?
How maximal is maximal mixing?.....

• Pending these questions many inventive models and elegant speculative solutions have been proposed.

• Experiments now running or being prepared or conceived can make neutrino oscillation measurements very precise and eliminate most models.

NEUTRINO PHYSICS WILL REMAIN A CENTRAL ISSUE IN PARTICLE PHYSICS IN THE NEXT DECADE(S).