Solutions to the Solar Neutrino Problem

Where do we stand ?

- ⋆ "Model Independent" Analysis
- ⋆ Energy Independent Solutions
- ⋆ MSW Effect
- ⋆ Vacuum Oscillations
- ⋆ "Exotic" Solutions

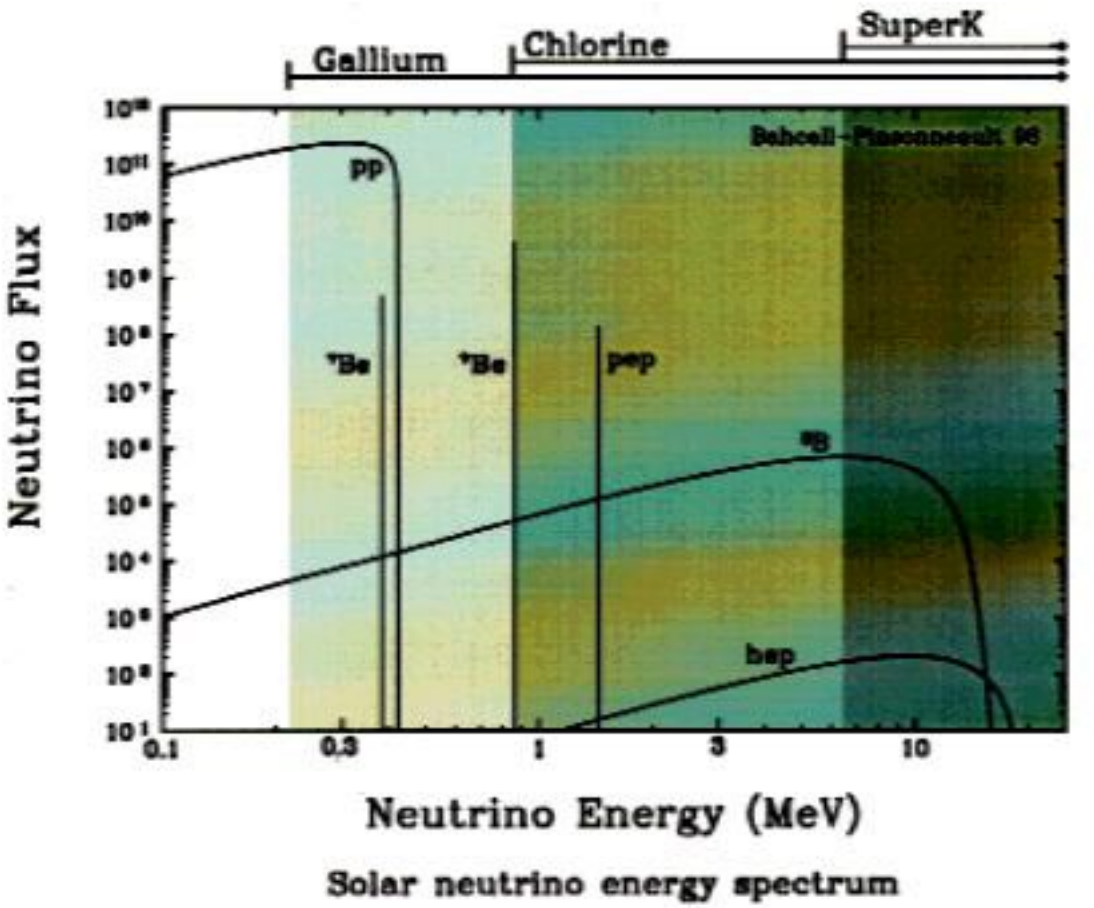
J. Bahcall
A. Smirnov

Solar Neutrino Experiments

- Three Experiments: E_{th}/MeV
  - Chlorine ($^{37}Cl(\nu_e, e)^{37}Ar$) 0.814
  - H_2O ($\nu + e^- \rightarrow \nu + e^-$) 5.5 (7.5)
  - Gallium ($^{71}Ga(\nu_e, e)^{71}Ge$) 0.233

- Measure Different Parts of the Solar Neutrino Spectrum

- Event Rates From Any Two Experiments Are Poorly Fitted Even With Free Fluxes



Solar neutrino energy spectrum

Solar Neutrino Data

- "Neutrino Summer 1999" data slightly different from "Neutrino '98" data
- SuperKamiokande:
  - 825 day of data (about 11000 events)
  - No spectral distortions
  - D-N effect $\approx 2\sigma$; Right Sign !
- Gallium detectors agree well (new SAGE result)
- Chlorine rate still the lowest

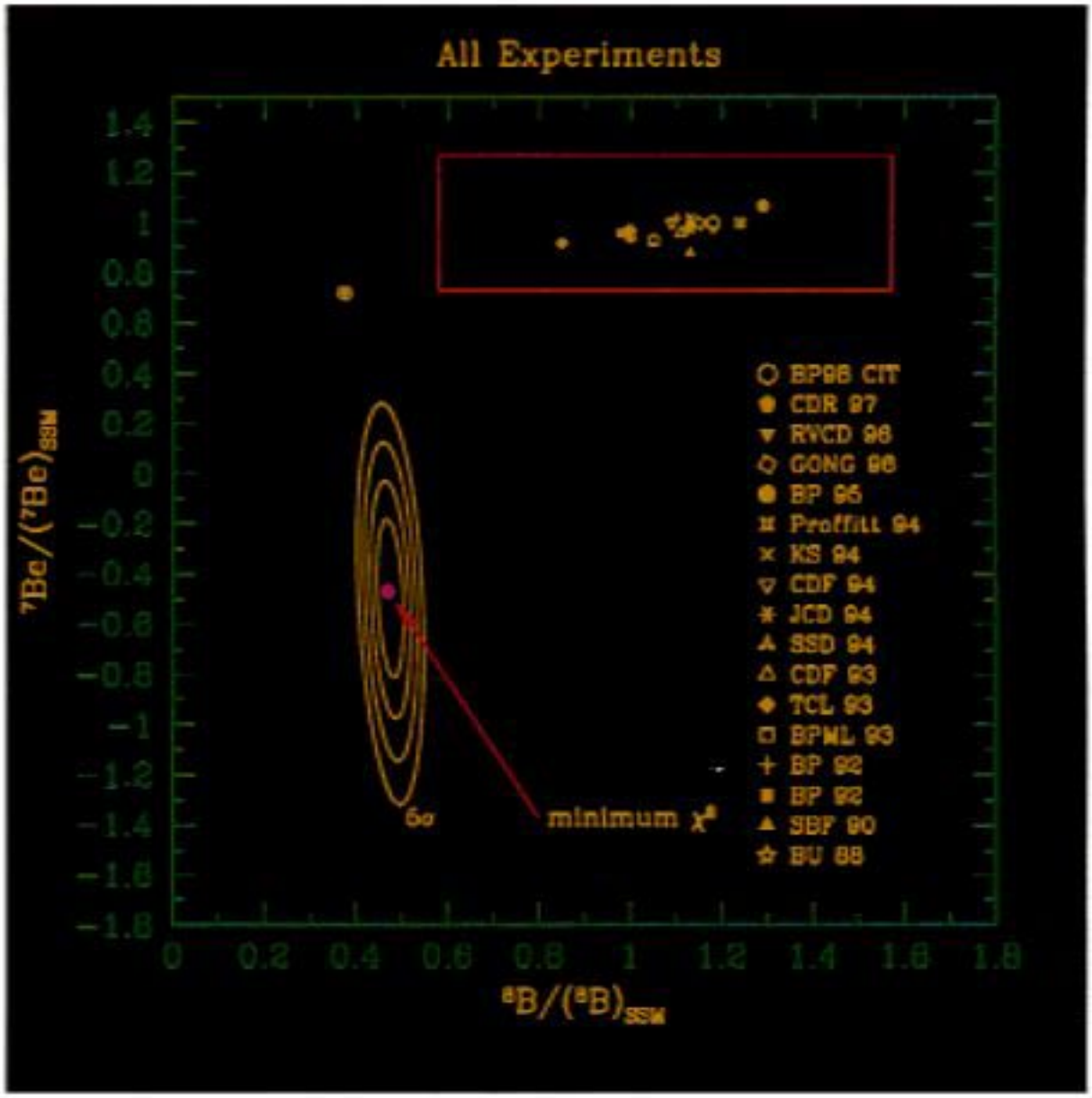
Experiment	Result	Theory	Result/Theory
Homestake	$2.56 \pm 0.16 \pm 0.14$	$7.7^{+1.2}_{-1.0}$	0.33 ± 0.028
Kamiokande	$2.80 \pm 0.19 \pm 0.33$	$5.15^{+1.0}_{-0.7}$	0.54 ± 0.07
SAGE	$67.2\ ^{+7.2}_{-7.0}\ ^{+3.5}_{-3.0}$	129^{+8}_{-6}	0.52 ± 0.06
GALLEX	$76.4 \pm 6.3\ ^{+4.5}_{-4.9}$	129^{+8}_{-6}	0.59 ± 0.06
SuperKamiokande	$2.45\ ^{+0.04}_{-0.04}\ ^{+0.07}_{-0.07}$	$5.15^{+1.0}_{-0.7}$	0.475 ± 0.015

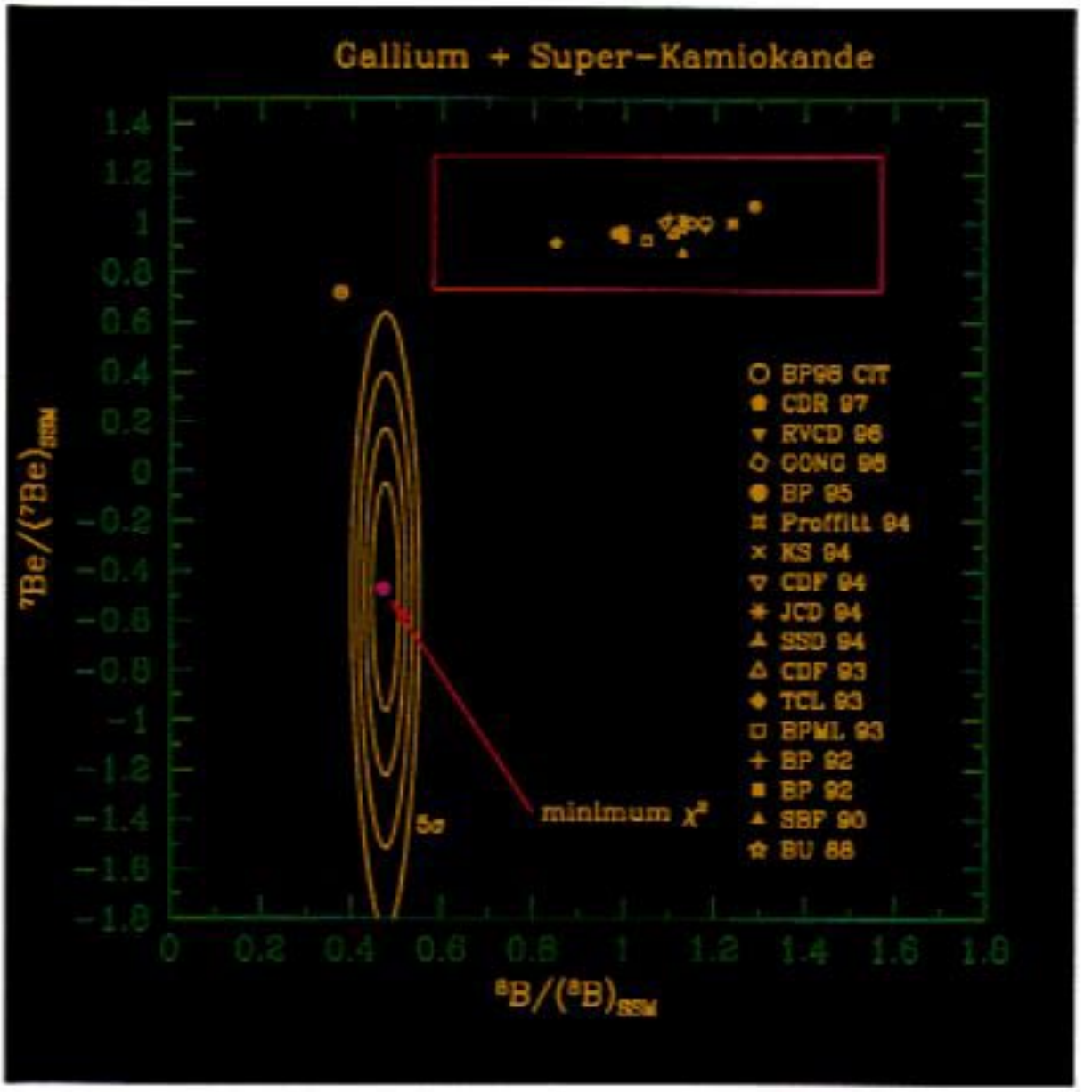
Model Independent Analysis

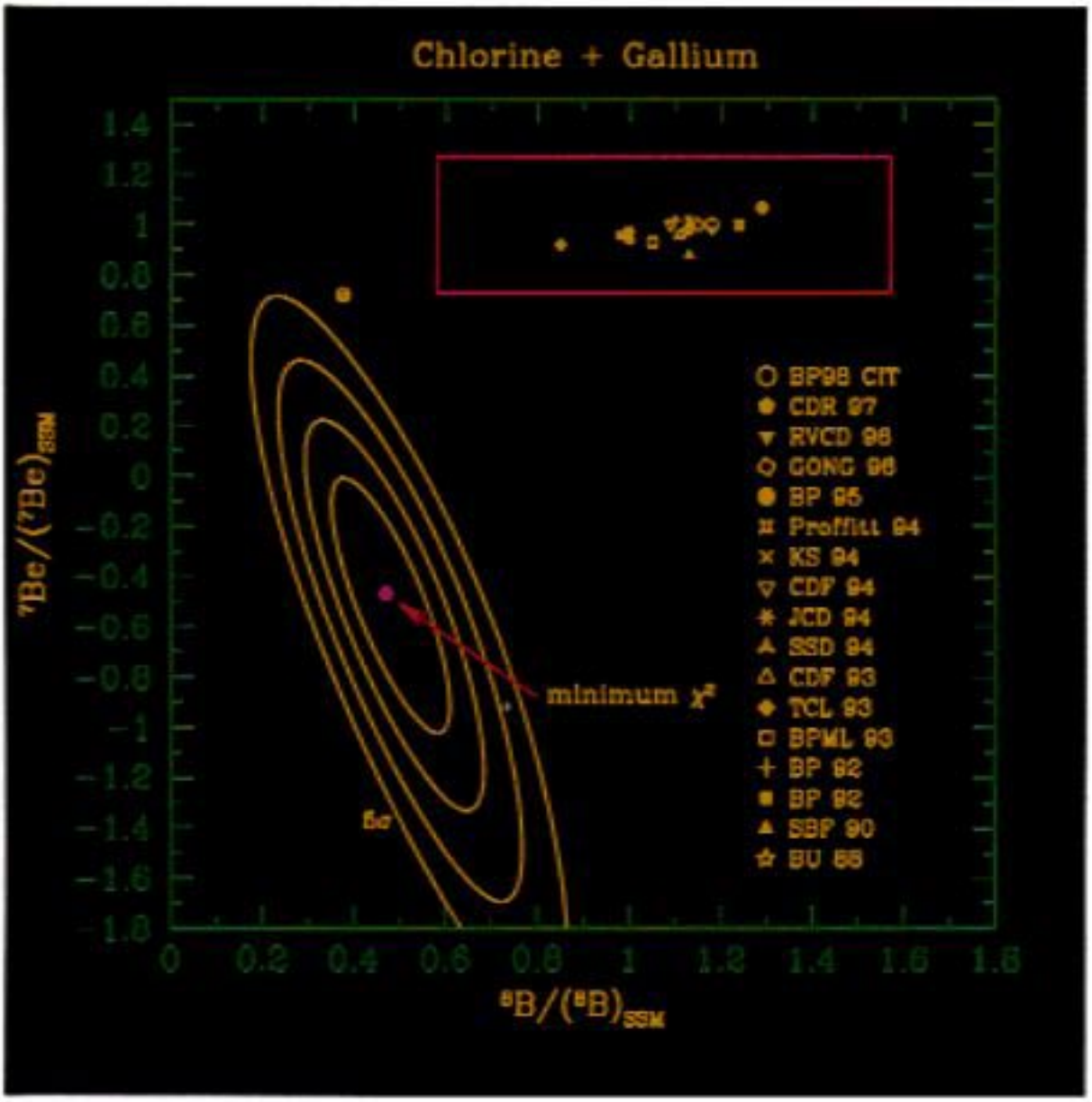
- Treat All ν Fluxes As Free Parameters
- With And Without Luminosity Constraint

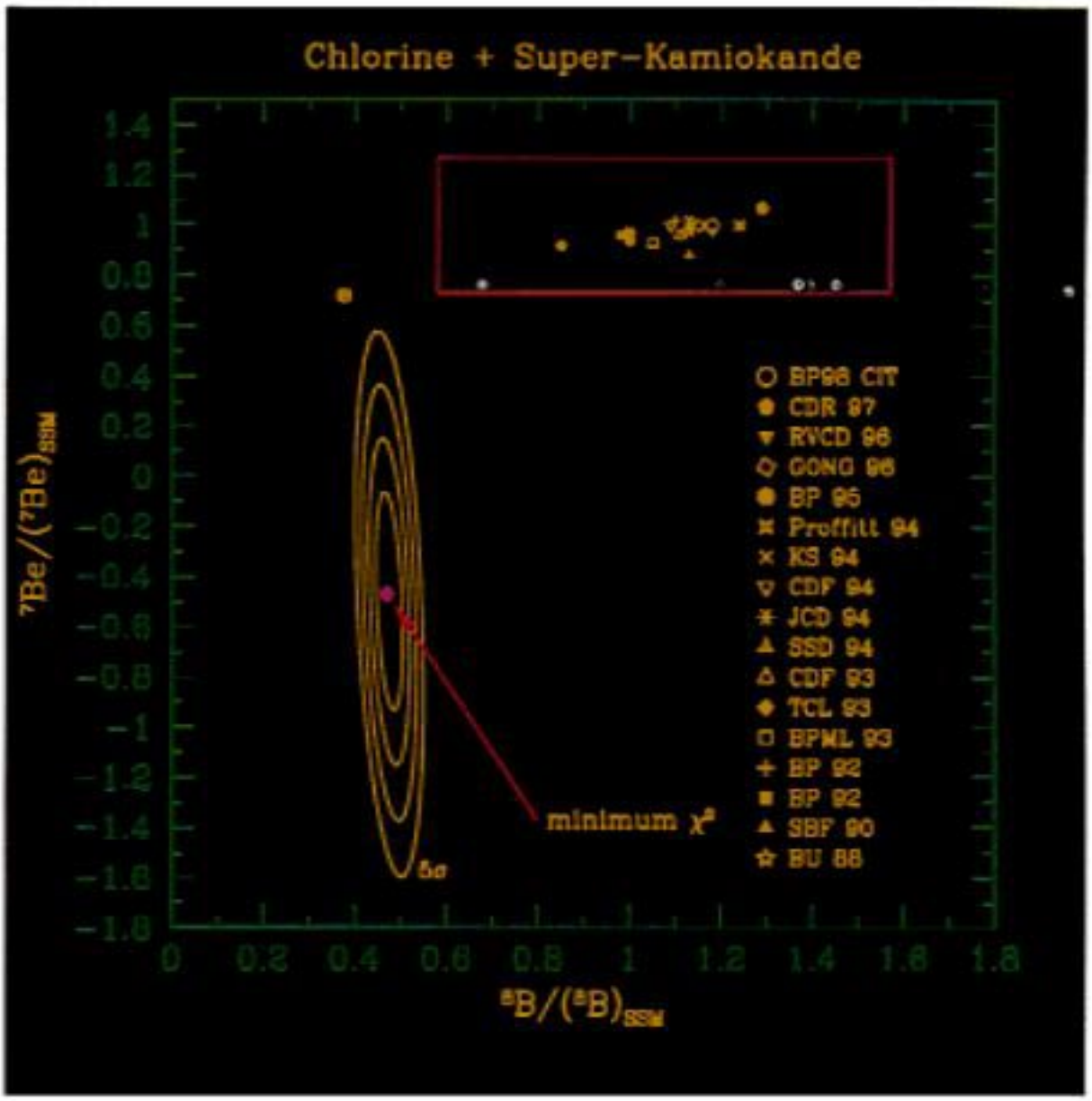
$$\sum \Phi_j \alpha_j = L_\odot / 4\pi r^2$$

- For Each Set of Fluxes Calculate R_i
- Compare R_i With Data


All Experiments
$^7Be/(^7Be)_{SSM}$
$^8B/(^8B)_{SSM}$
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
6σ
minimum χ^2
BP98 CIT
CDR 97
RVCD 96
GONG 96
BP 95
Proffitt 94
KS 94
CDF 94
JCD 94
SSD 94
CDF 93
TCL 93
BPML 93
BP 92
BP 92
SBF 90
BU 88


Gallium + Super-Kamiokande
$^7Be/(^7Be)_{SSM}$
$^8B/(^8B)_{SSM}$
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
5σ
minimum χ^2
BP98 CIT
CDR 97
RVCD 96
CONC 96
BP 95
Proffitt 94
KS 94
CDF 94
JCD 94
SSD 94
CDF 93
TCL 93
BPML 93
BP 92
BP 92
SBF 90
BU 88


Chlorine + Gallium
BP98 CIT
CDR 97
RVCD 96
GONG 96
BP 95
Proffitt 94
KS 94
CDF 94
JCD 94
SSD 94
CDF 93
TCL 93
BPML 93
BP 92
BP 92
SBP 90
BU 88
minimum χ²
5σ
$^7Be/(^7Be)_{SSM}$
$^8B/(^8B)_{SSM}$


Chlorine + Super-Kamiokande
$^7Be/(^7Be)_{SSM}$
$^8B/(^8B)_{SSM}$
minimum χ^2
5σ
BP98 CIT
CDR 97
RVCD 96
GONG 96
BP 95
Proffitt 94
KS 94
CDF 94
JCD 94
SSD 94
CDF 93
TCL 93
BPNL 93
BP 92
BP 92
SBF 90
BU 88

Energy independent solutions

- What if $\nu_e \to \nu_x$ but $P(\nu_e \to \nu_e) = const$?
- Not Equivalent To "Model Independent"
- ONLY IF $\nu_x \equiv \nu_{st}$ AND

  Luminosity Constraint Neglected THEN

  Energy Independent Is Covered By

  Model Independent

Active Neutrinos

	fixed ^{8}B flux		free ^{8}B flux	
Scenario	**min χ^2**	**C.L. (%)**	**min χ^2**	**C.L. (%)**
$0 < P < 1$	**13.8**	**99.90**	**13.2**	**99.97**
$P = 1/3$	**27.0**	**99.9999**	**26.6**	**99.9999**
$P = 1/2$	**14.0**	**99.91**	**13.2**	**99.97**
$P = 5/9$	**16.4**	**99.97**	**15.2**	**99.99**

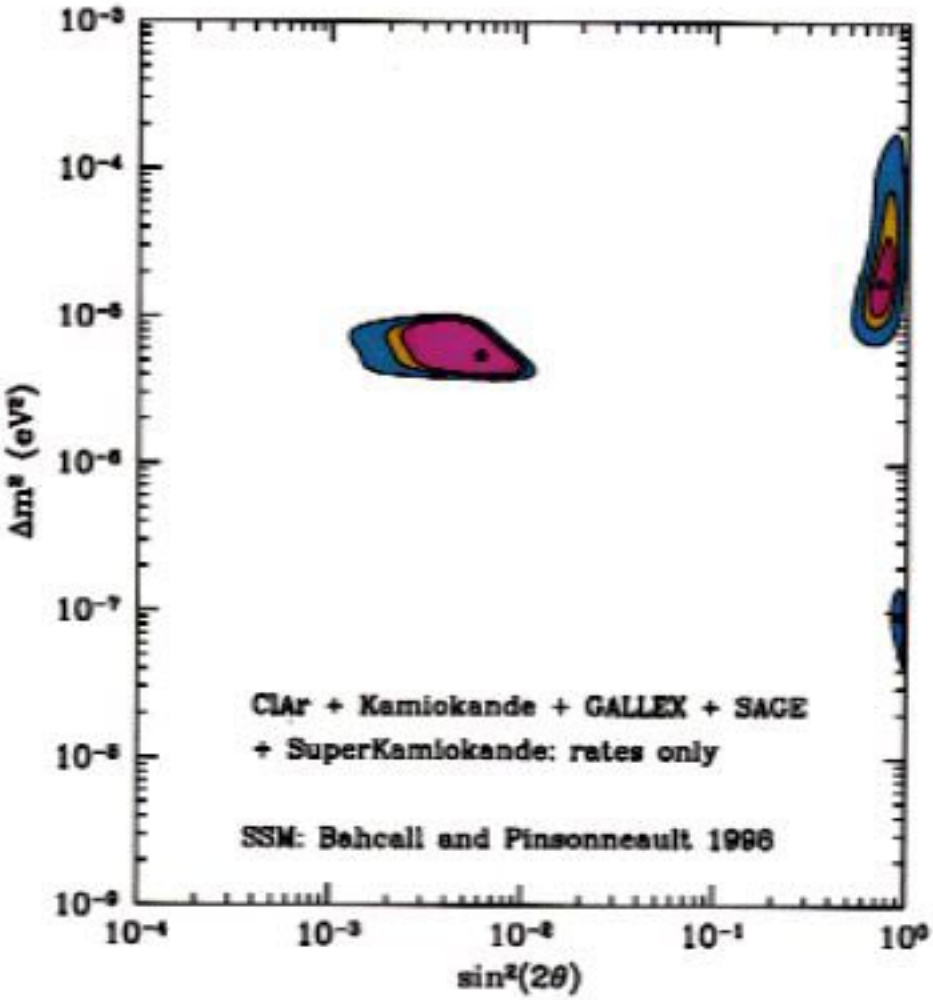
Sterile Neutrinos

Scenario	fixed ^8B flux min χ^2	fixed ^8B flux C.L. (%)	free ^8B flux min χ^2	free ^8B flux C.L. (%)
$0 < P < 1$	23.5	99.999	23.5	99.9999
$P = 1/3$	41.4	> 99.99999	34.3	> 99.99999
$P = 1/2$	23.1	99.999	23.0	99.9998
$P = 5/9$	24.3	99.9995	24.3	99.9999

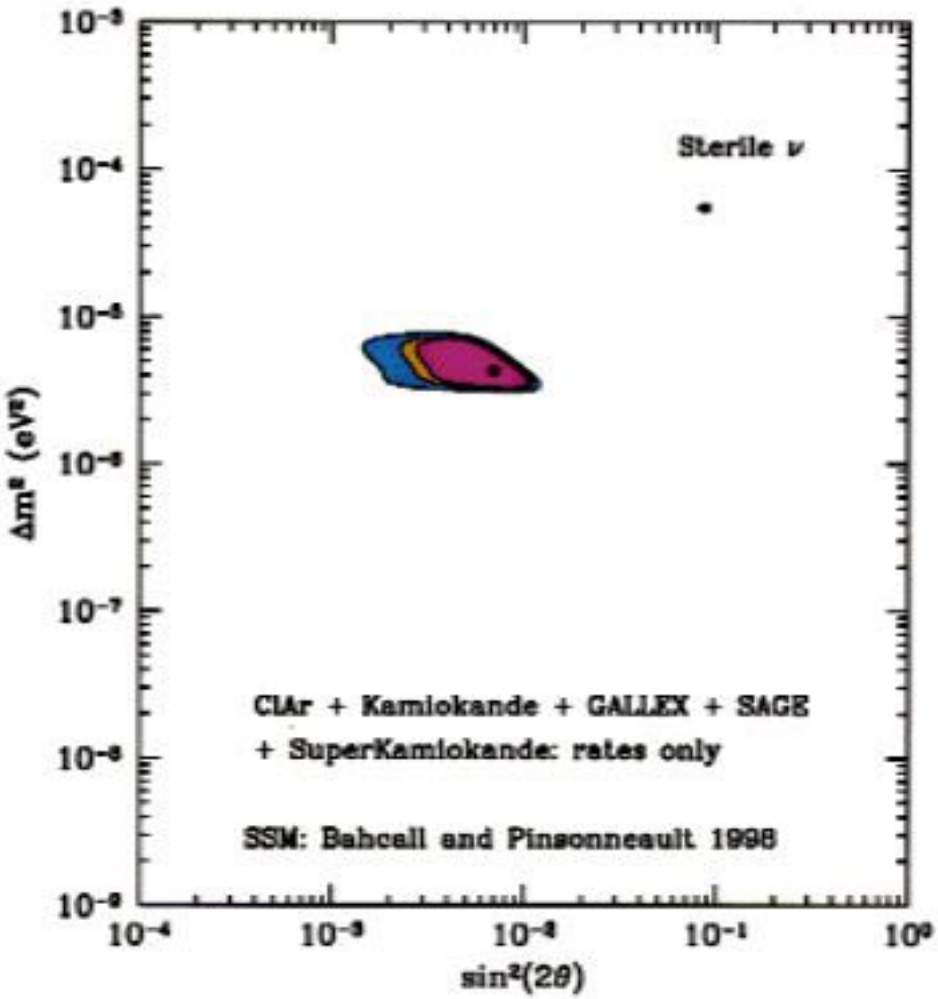
MSW Solutions ($\nu_e \to \nu_a$)

- Include Spectrum, Zenith Angle and D/N data from SuperKamiokande
- Latest Rates Data
- Standard Solar Model by BP '98
- Accurate Treatment of Earth Effect
- Precise Neutrino Cross-Sections

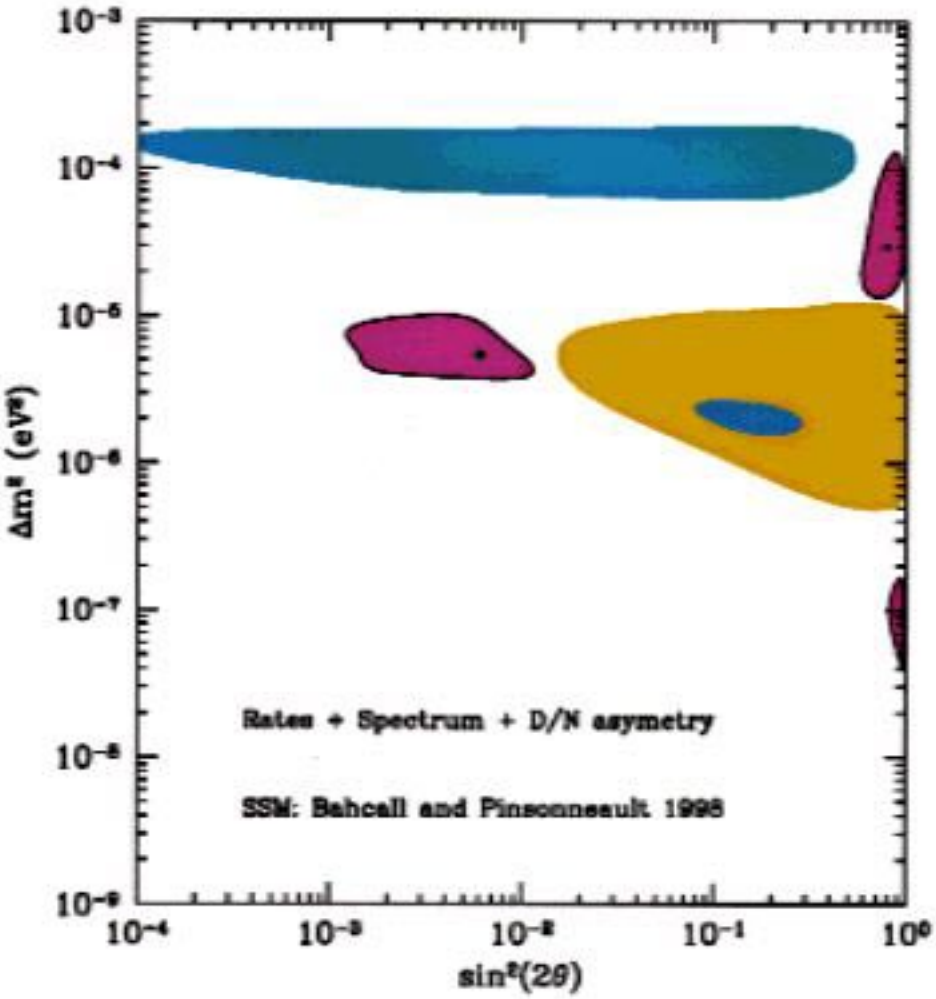
MSW Allowed Regions ($\nu_e \to \nu_a$)



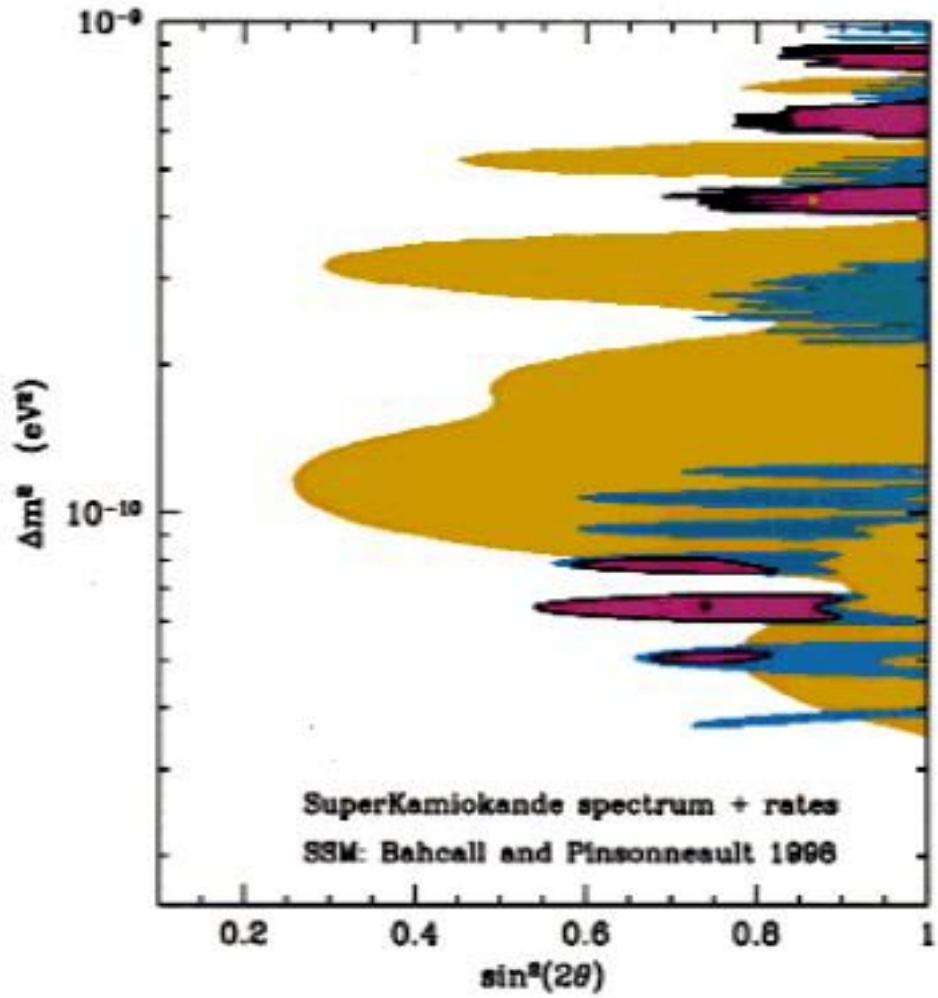
MSW Allowed Regions ($\nu_e \rightarrow \nu_{st}$)

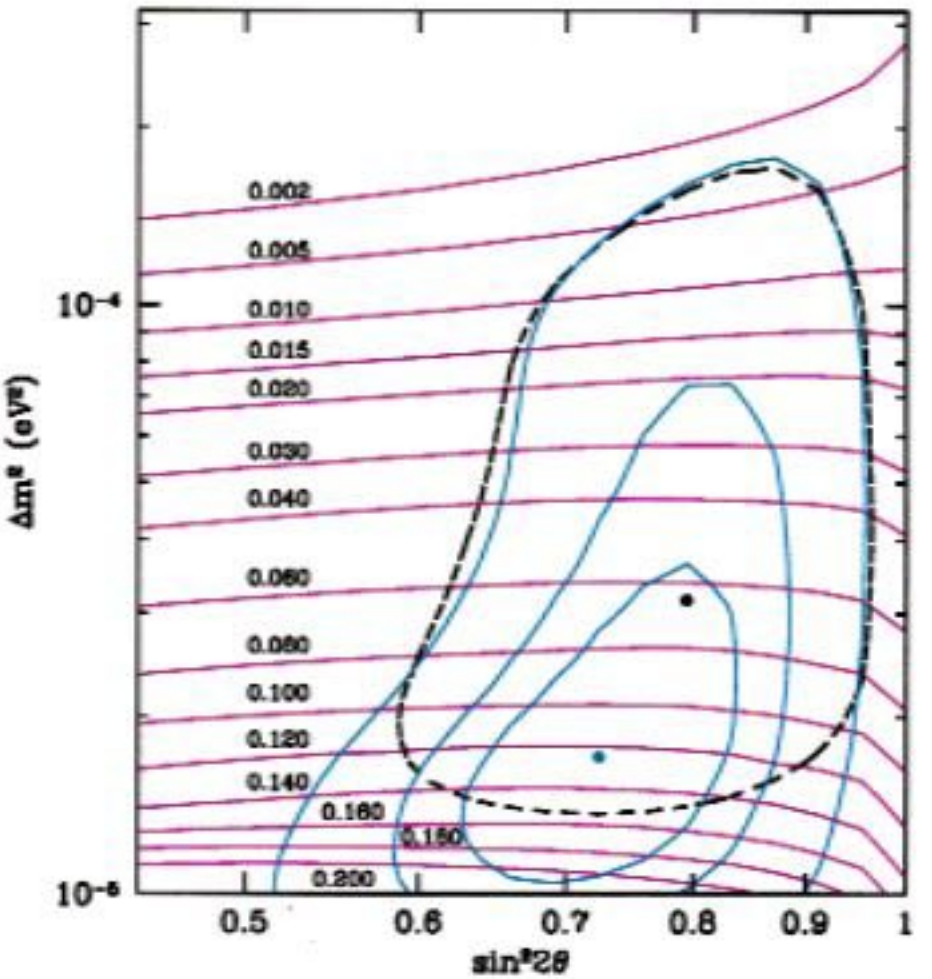


Global Fit (MSW)

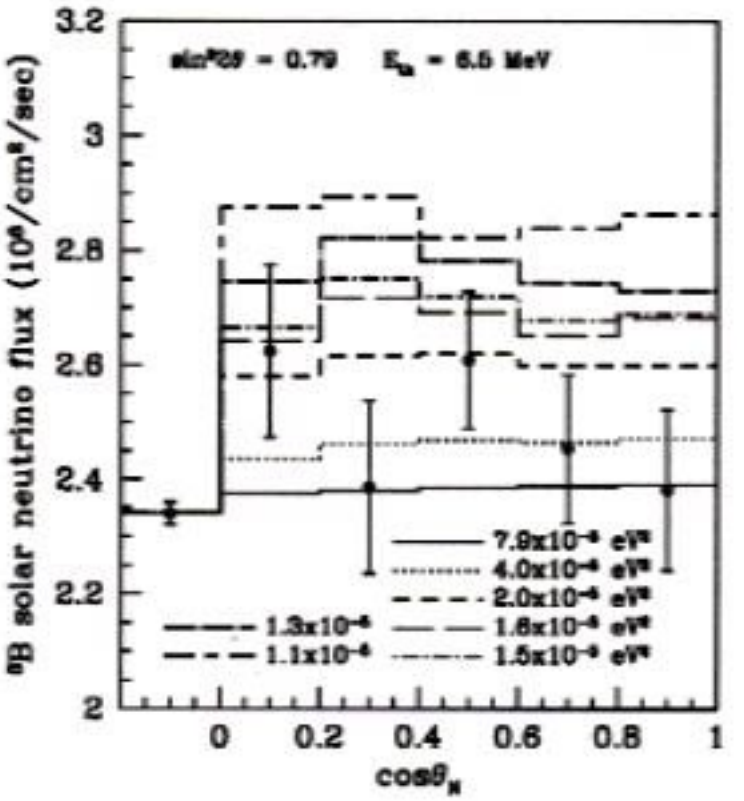


Global Fit (VAC)

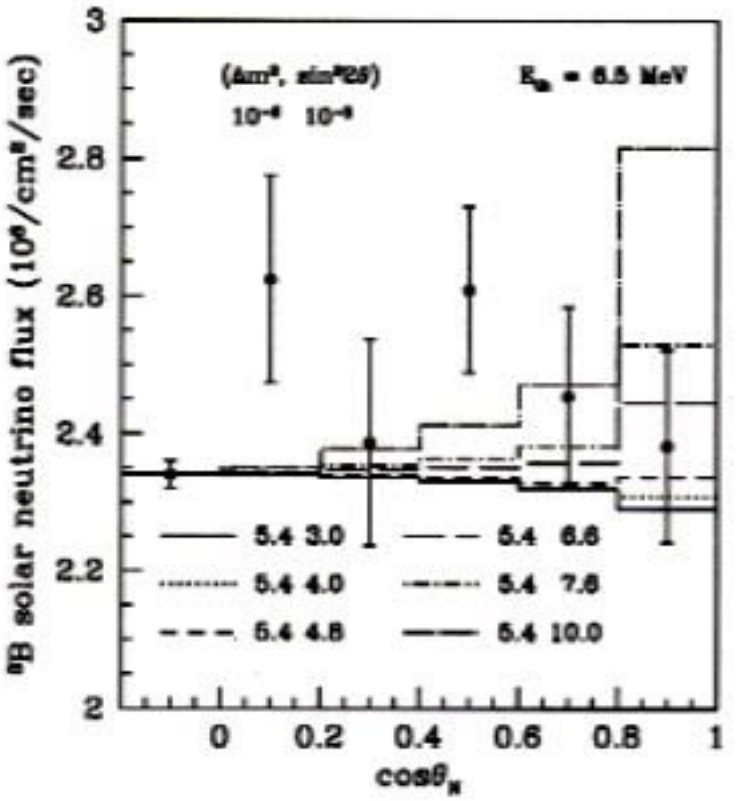



0.002
0.005
0.010
0.015
0.020
0.030
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
10^{-4}
10^{-5}
Δm^2 (eV^2)
0.5
0.6
0.7
0.8
0.9
1
$\sin^2 2\theta$

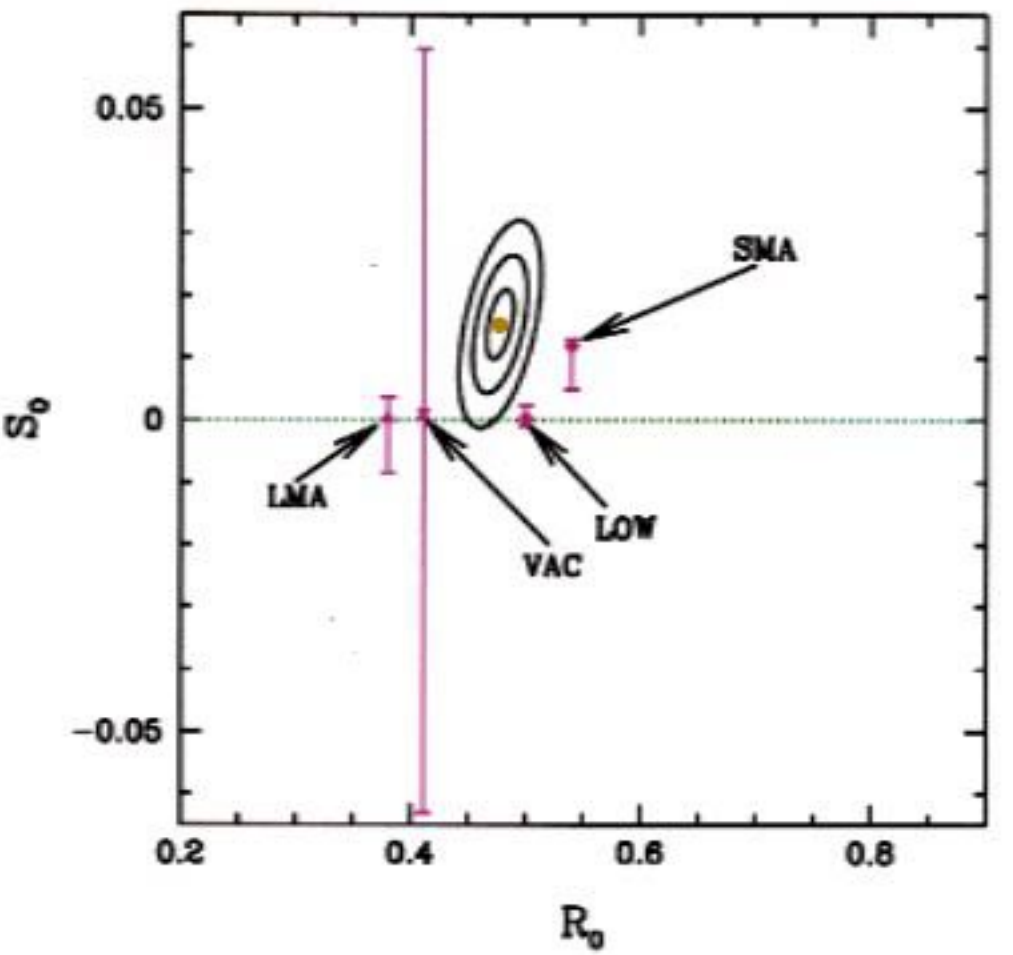
Zenith Angle Distribution (LMA)



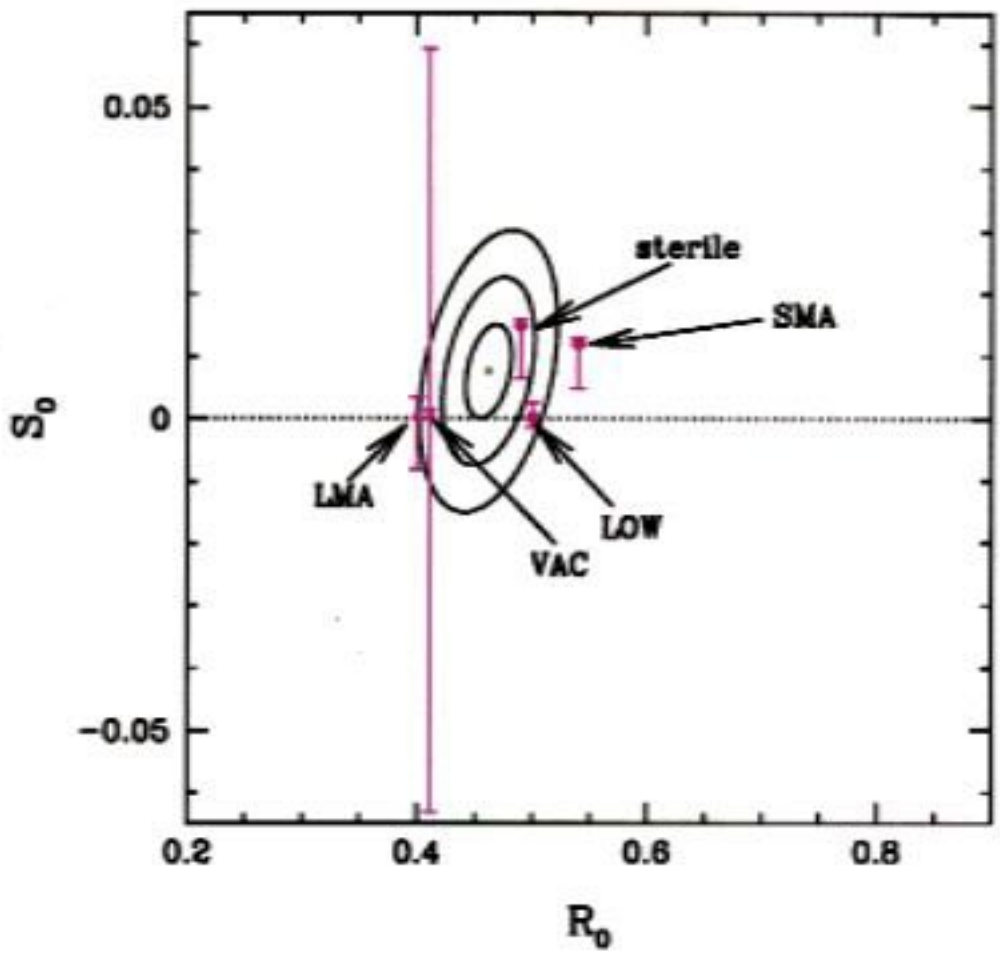
Zenith Angle Distribution (SMA)



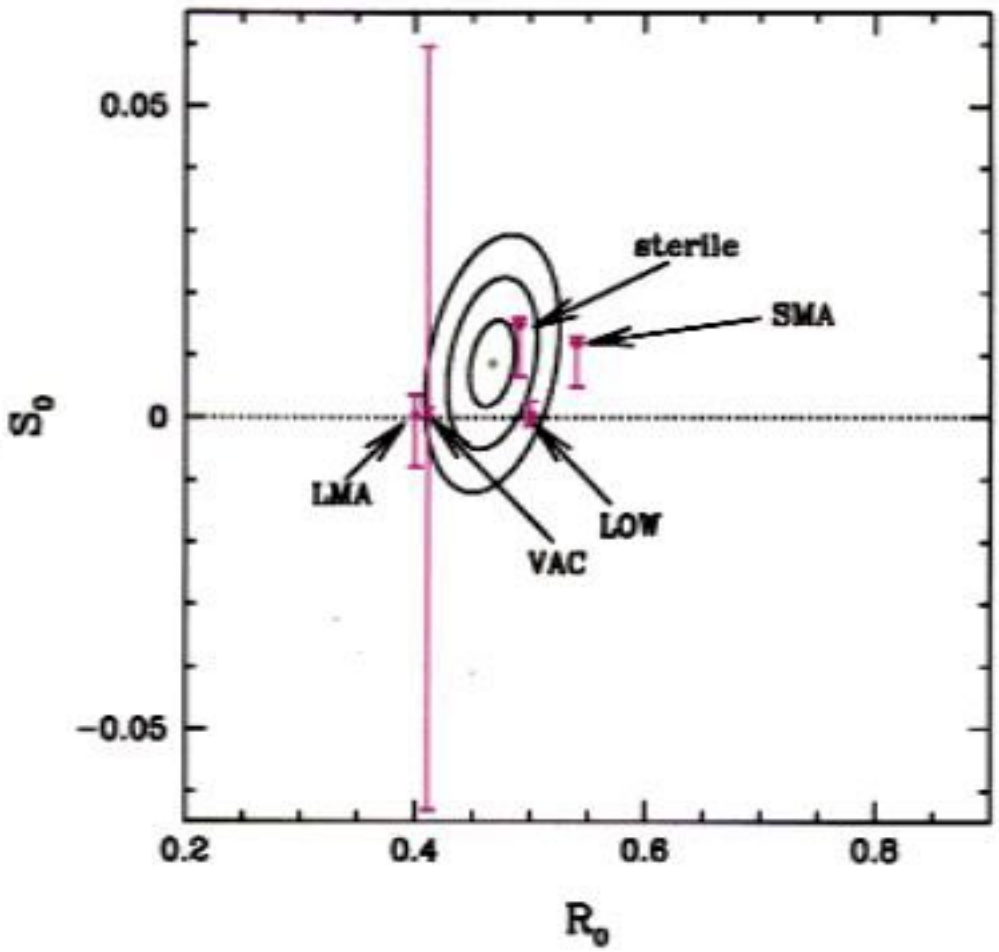
Line Fit to the Spectrum (504 days)



Line Fit to the Spectrum (708 days)

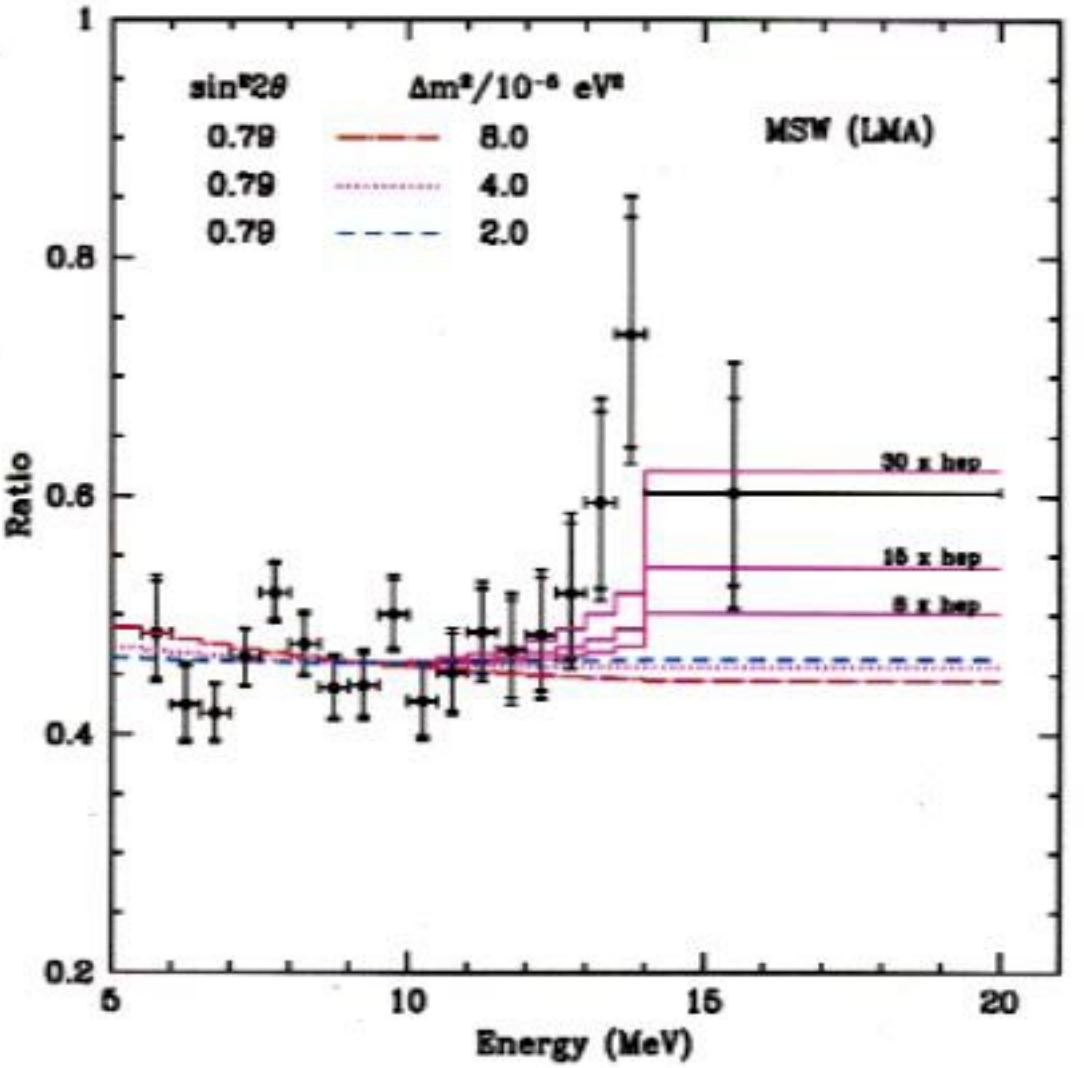


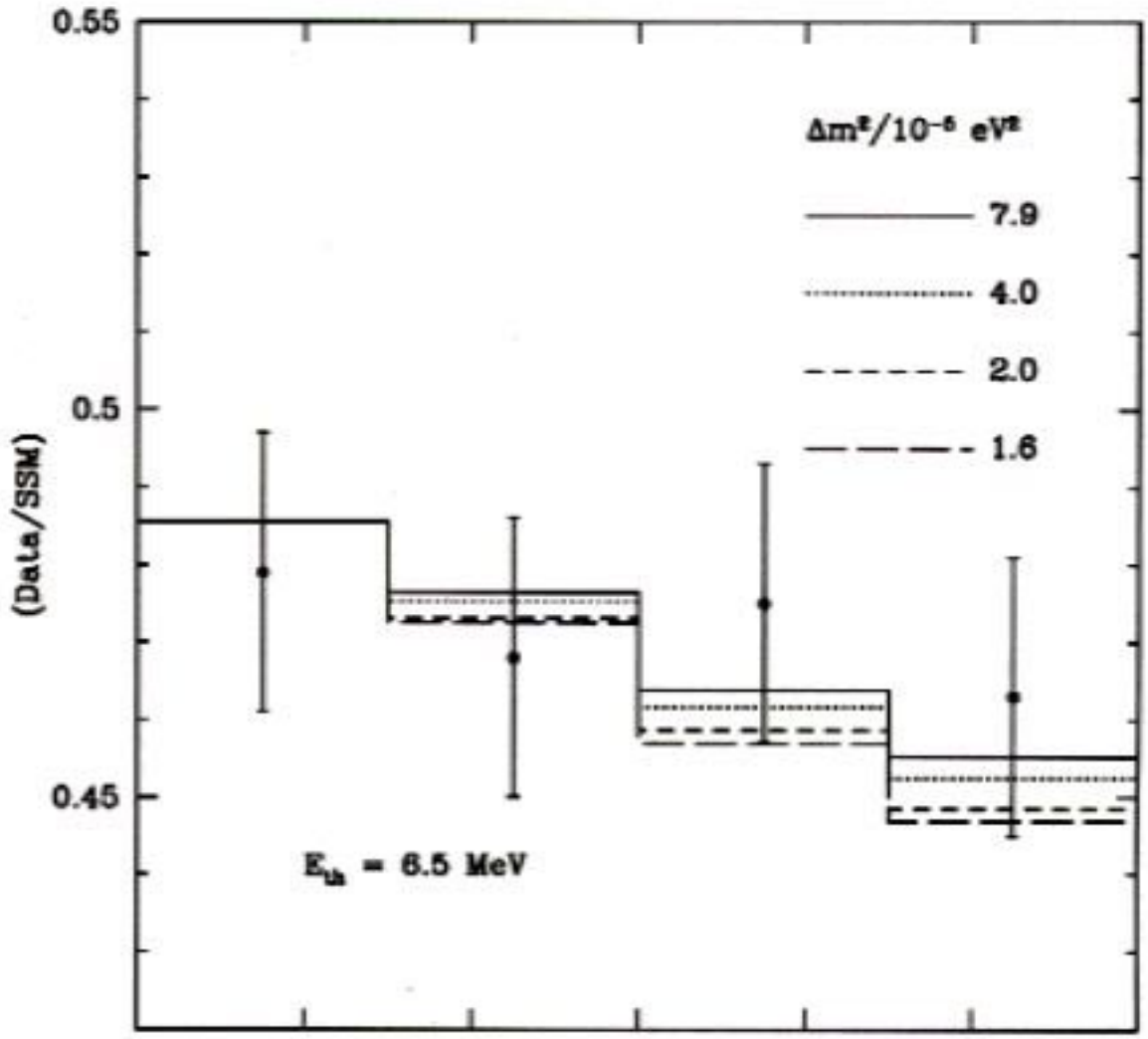
Line Fit to the Spectrum (708 days)

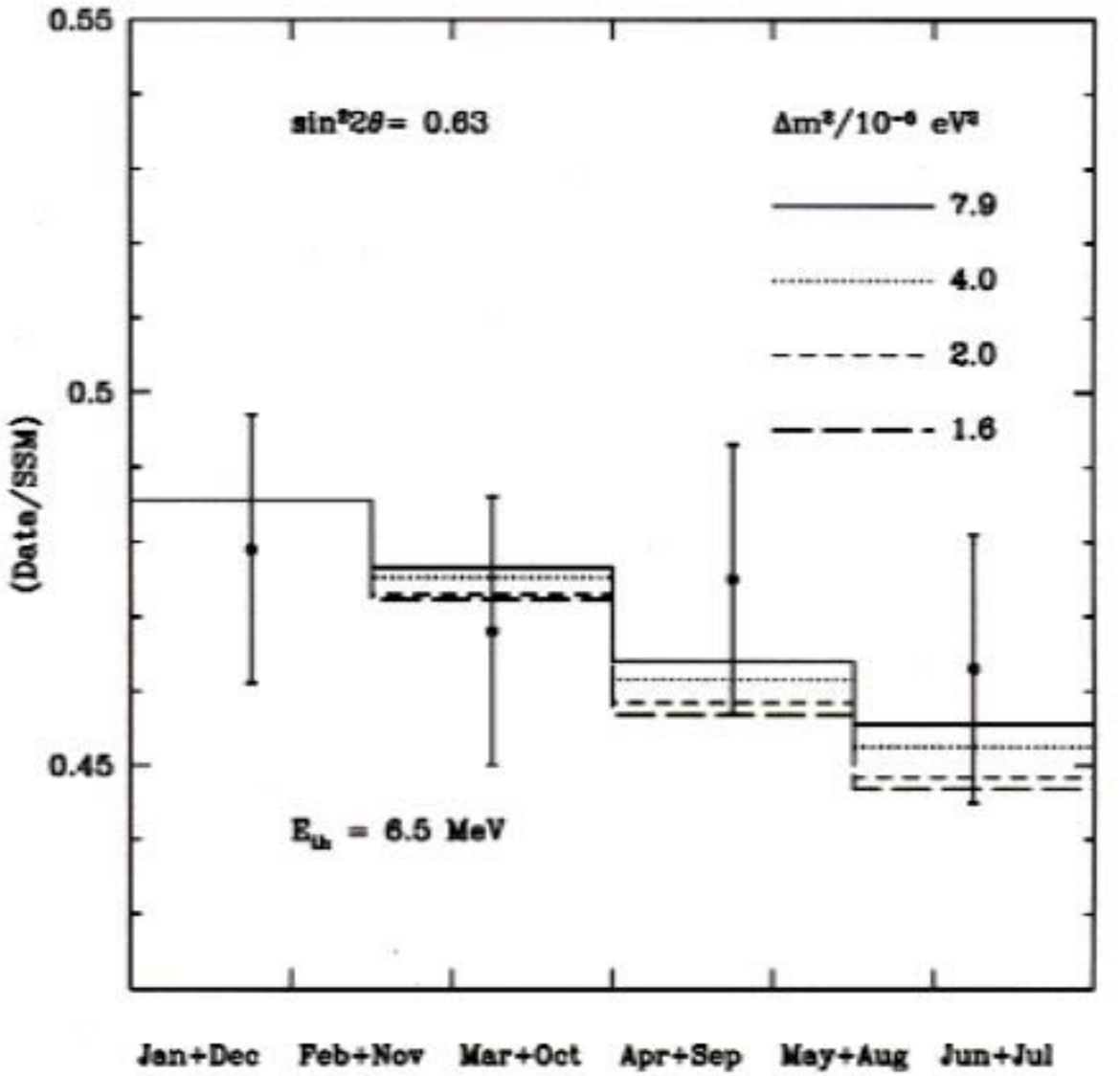


Hep Neutrinos

- $^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$
- *hep* Spectrum: End Point 18.6 MeV
- Flux of *hep* neutrinos VERY uncertain
- A High *hep* Neutrino Flux Can
  - Explain High Energy Part of Spectrum
  - Save LMA and LOW Solutions

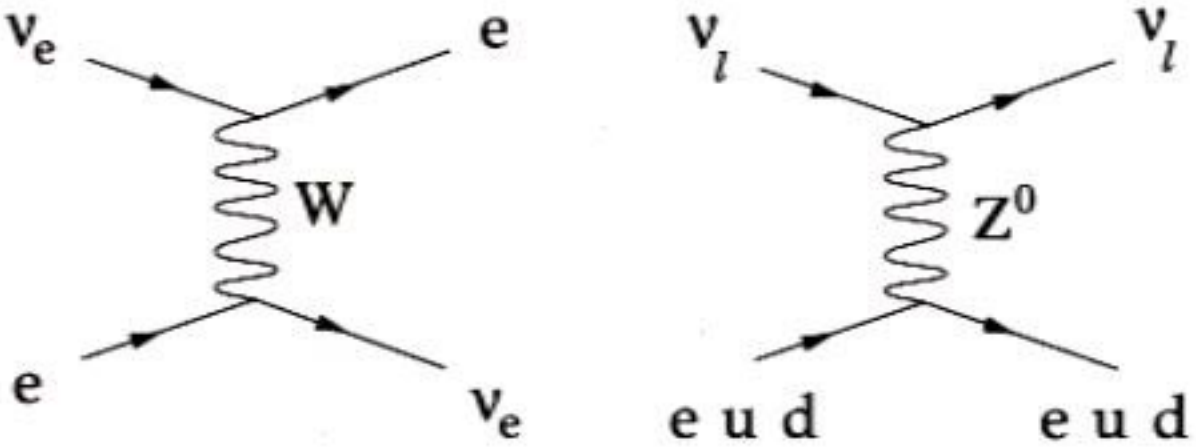

sin²2θ
Δm²/10⁻⁵ eV²
0.79
8.0
0.79
4.0
0.79
2.0
MSW (LMA)
30 x hep
15 x hep
8 x hep
Ratio
Energy (MeV)
1
0.8
0.6
0.4
0.2
5
10
15
20


0.55
0.5
0.45
(Data/SSM)
Δm²/10⁻⁵ eV²
7.9
4.0
2.0
1.6
E_th = 6.5 MeV
Jan+Dec
Feb+Nov
Mar+Oct
Apr+Sep
May+Aug
Jun+Jul


0.55
0.5
0.45
(Data/SSM)
sin²2θ= 0.63
Δm²/10⁻⁶ eV²
7.9
4.0
2.0
1.6
E_th = 6.5 MeV
Jan+Dec
Feb+Nov
Mar+Oct
Apr+Sep
May+Aug
Jun+Jul

Standard Electroweak Interactions

MSW

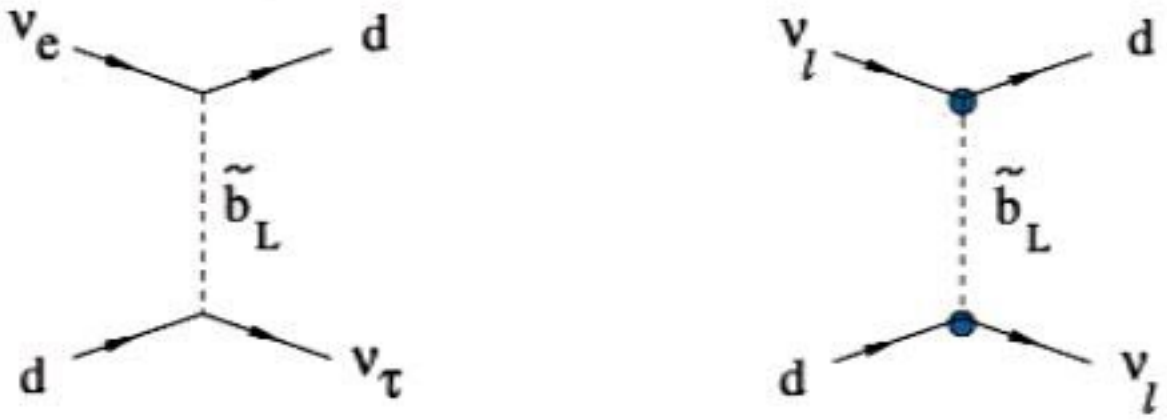


Wolfenstein

Mikheyev and Smirnov

Flavor Changing Neutral Currents

FCNC + FDNC

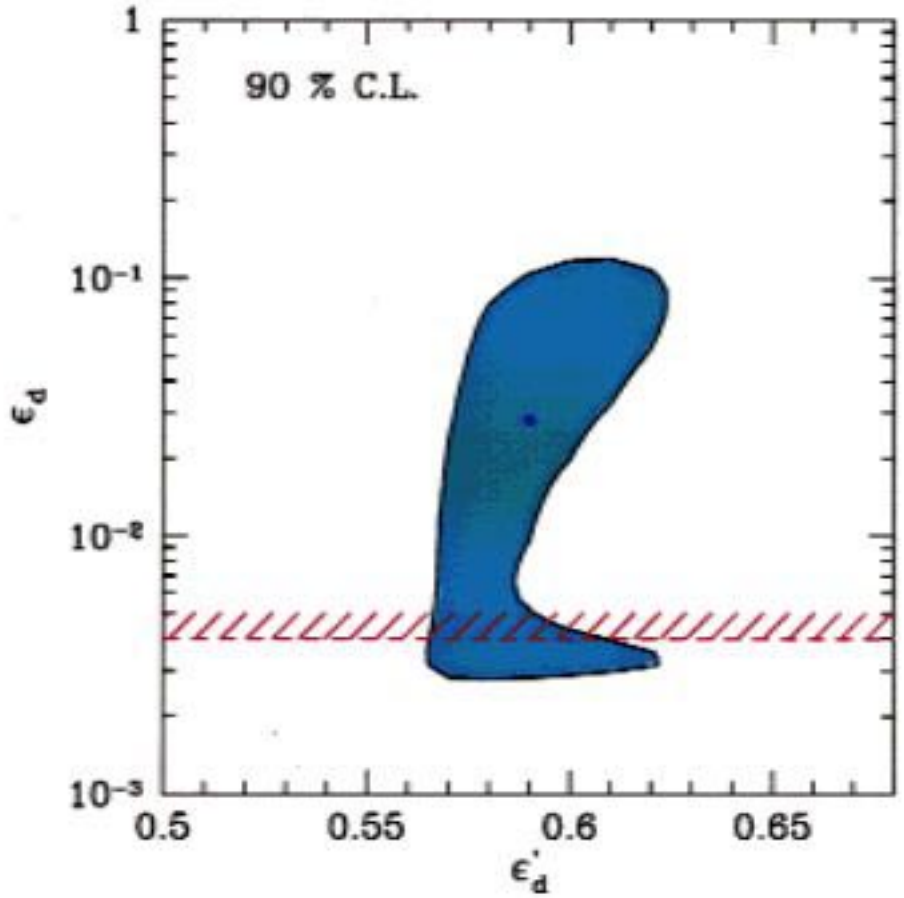


Roulet

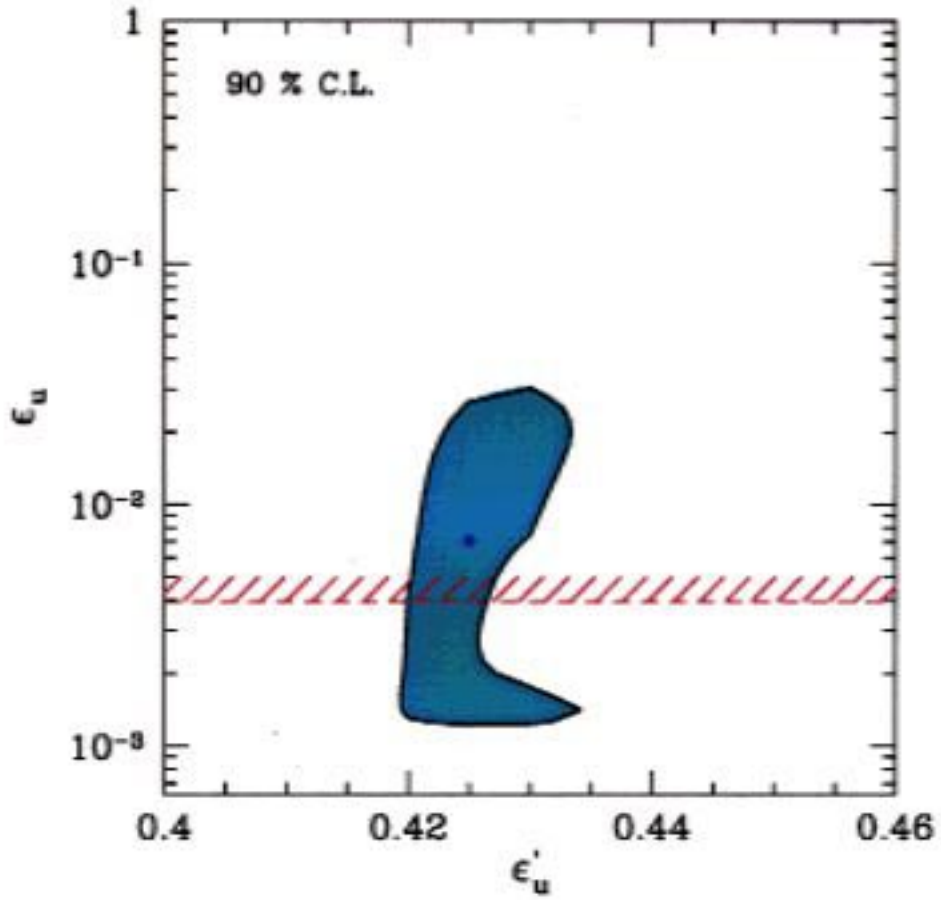
Guzzo, Masiero and Petcov

Barger, Phillips and Whisnant

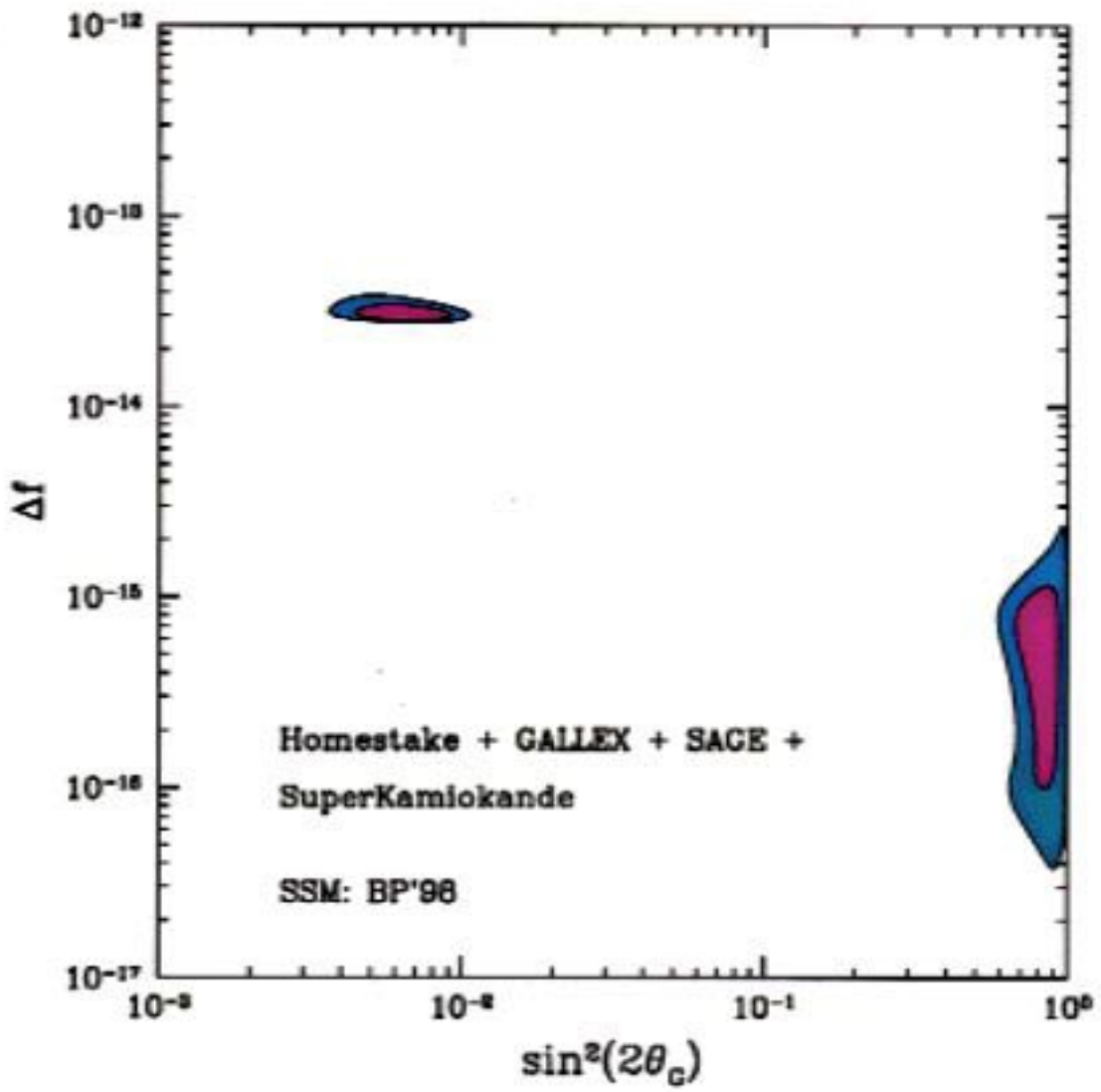
Flavor Changing Neutral Currents



Flavor Changing Neutral Currents



Violation of the Equivalence Principle



Summary

- No "Smoking Gun" Yet
- No Real Alternative to Oscillations
- Global Analysis Becomes Important
- More Experiments Even More Important !