

Neutrino Physics

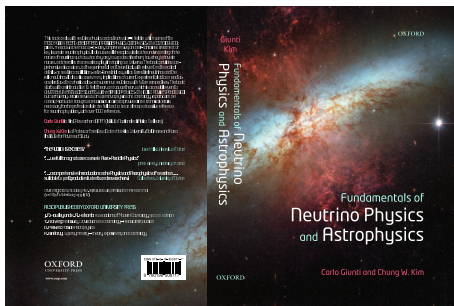
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Neutrino Unbound: <http://www.nu.to.infn.it>

Doctoral Program in Physics, EPFL, Lausanne, May 2011



C. Giunti and C.W. Kim
Fundamentals of Neutrino Physics
and Astrophysics
Oxford University Press
15 March 2007 – 728 pages

Part I: Theory of Neutrino Masses and Mixing

- Dirac Neutrino Masses and Mixing
- Majorana Neutrino Masses and Mixing
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- Solar Neutrinos and KamLAND
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- Phenomenology of Three-Neutrino Mixing
- Absolute Scale of Neutrino Masses
- Anomalies Beyond Three-Neutrino Mixing
- Conclusions

Part III

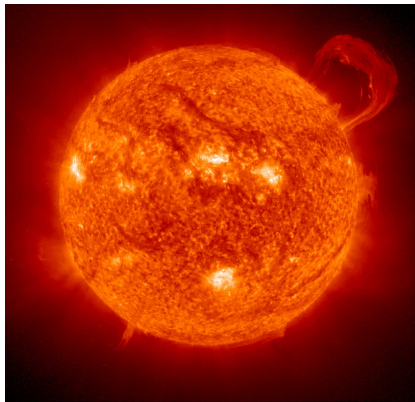
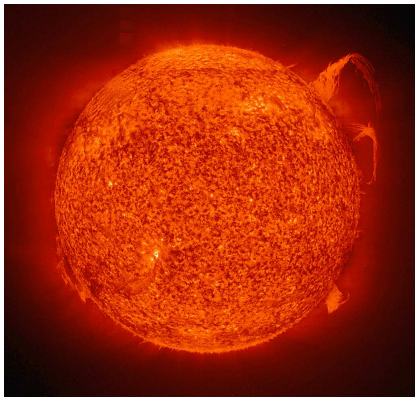
Phenomenology

- Solar Neutrinos and KamLAND
- Atmospheric and LBL Oscillation Experiments
- Phenomenology of Three-Neutrino Mixing
- Absolute Scale of Neutrino Masses
- Anomalies Beyond Three-Neutrino Mixing
- Conclusions

Solar Neutrinos and KamLAND

- Solar Neutrinos and KamLAND
 - The Sun
 - Standard Solar Model (SSM)
 - Homestake
 - Gallium Experiments
 - SAGE: Soviet-American Gallium Experiment
 - GALLEX: GALLium EXperiment
 - GNO: Gallium Neutrino Observatory
 - Kamiokande
 - Super-Kamiokande
 - SNO: Sudbury Neutrino Observatory
 - KamLAND
 - Sterile Neutrinos in Solar Neutrino Flux?
 - Determination of Solar Neutrino Fluxes
 - Details of Solar Neutrino Oscillations
 - BOREXino

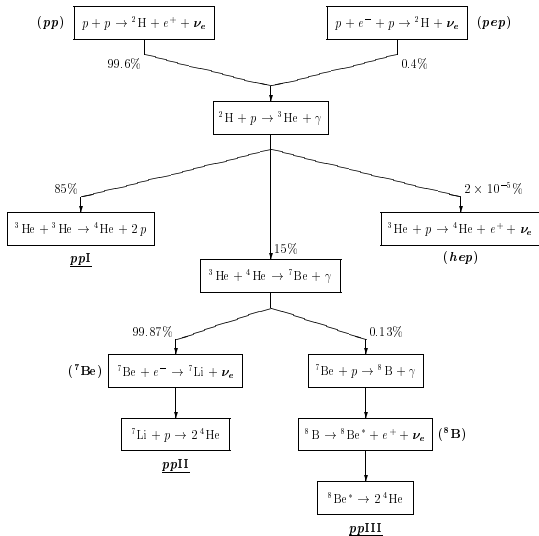
The Sun



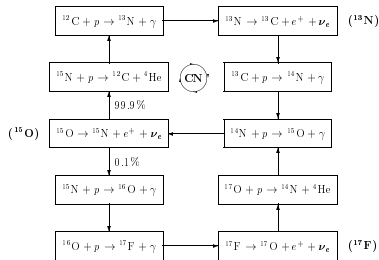
Extreme ultraviolet Imaging Telescope (EIT) 304 Å images of the Sun emission in this spectral line (He II) shows the upper chromosphere at a temperature of about 60,000 K

[The Solar and Heliospheric Observatory (SOHO), <http://sohowww.nascom.nasa.gov/>]

Standard Solar Model (SSM)

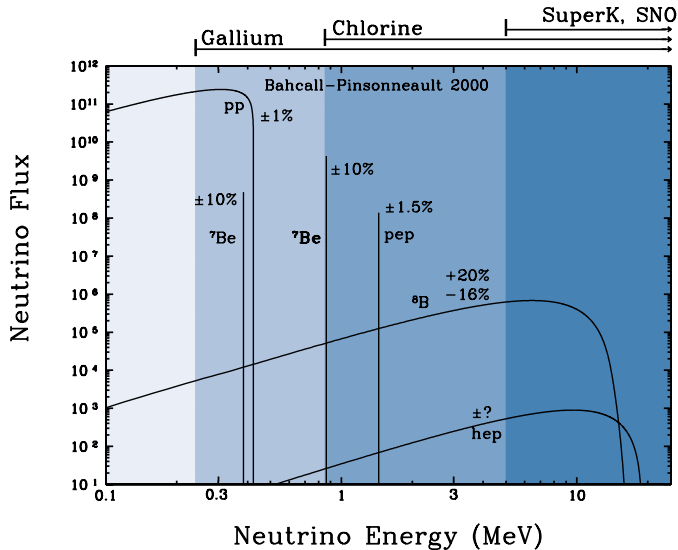


pp chain and CNO cycle

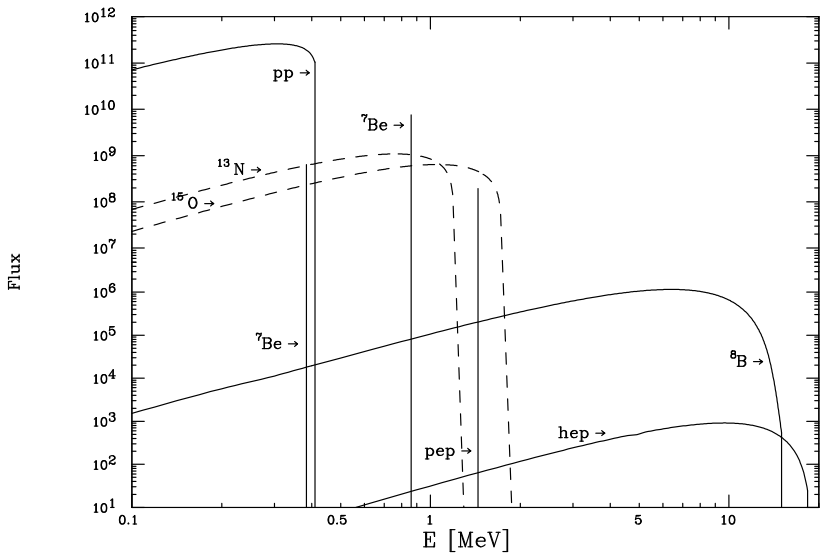


Bahcall SSMs

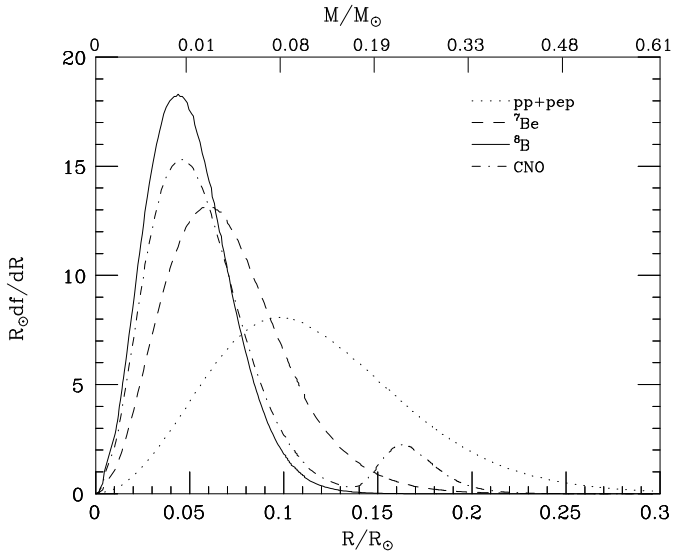
[J.N. Bahcall, <http://www.sns.ias.edu/~jnb>]



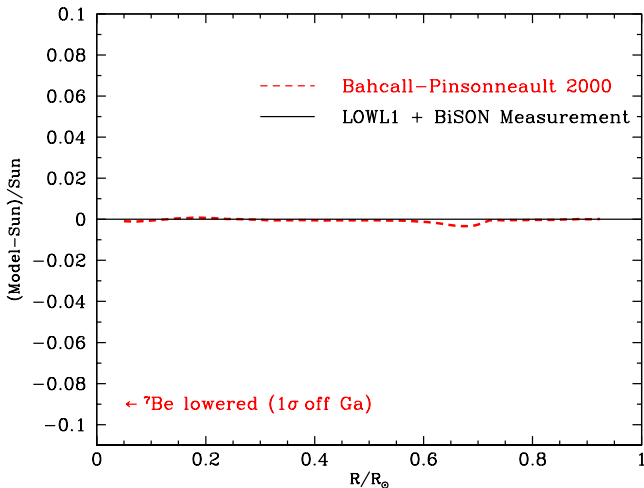
[J.N. Bahcall, <http://www.sns.ias.edu/~jnb>]



[Castellani, Degl'Innocenti, Fiorentini, Lissia, Ricci, Phys. Rept. 281 (1997) 309, astro-ph/9606180]



[Castellani, Degl'Innocenti, Fiorentini, Lissia, Ricci, Phys. Rept. 281 (1997) 309, astro-ph/9606180]



[J.N. Bahcall, <http://www.sns.ias.edu/~jnb>]

predicted versus measured sound speed

the rms fractional difference between the calculated and the measured sound speeds is 0.10% for all solar radii between between $0.05 R_{\odot}$ and $0.95 R_{\odot}$ and is 0.08% for the deep interior region, $r < 0.25 R_{\odot}$, in which neutrinos are produced

Homestake

$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$ [Pontecorvo (1946), Alvarez (1949)] radiochemical experiment

Homestake Gold Mine (South Dakota)

1478 m deep, 4200 m.w.e. $\Rightarrow \Phi_\mu \simeq 4 \text{ m}^{-2} \text{ day}^{-1}$

steel tank, 6.1 m diameter, 14.6 m long (6×10^5 liters)

615 tons of tetrachloroethylene (C_2Cl_4), 2.16×10^{30} atoms of ${}^{37}\text{Cl}$ (133 tons)

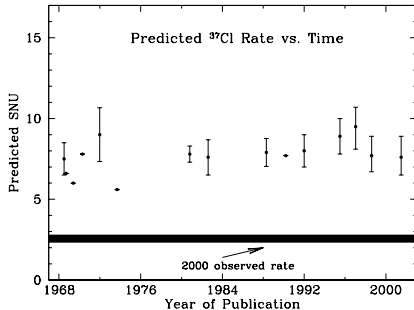
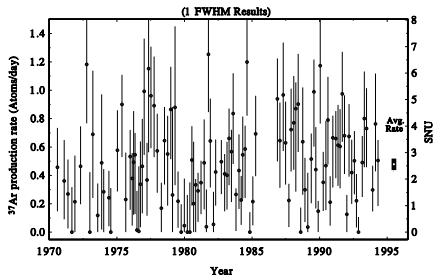
energy threshold: $E_{\text{th}}^{\text{Cl}} = 0.814 \text{ MeV} \Rightarrow {}^8\text{B}, {}^7\text{Be}, \text{pep}, \text{hep}, {}^{13}\text{N}, {}^{15}\text{O}, {}^{17}\text{F}$

1970–1994, 108 extractions $\Rightarrow \frac{R_{\text{Cl}}^{\text{exp}}}{R_{\text{Cl}}^{\text{SSM}}} = 0.34 \pm 0.03$ [APJ 496 (1998) 505]

$$R_{\text{Cl}}^{\text{exp}} = 2.56 \pm 0.23 \text{ SNU}$$

$$R_{\text{Cl}}^{\text{SSM}} = 7.6_{-1.1}^{+1.3} \text{ SNU}$$

$$1 \text{ SNU} = 10^{-36} \text{ events atom}^{-1} \text{ s}^{-1}$$



Gallium Experiments

SAGE, GALLEX, GNO

radiochemical experiments



threshold: $E_{\text{th}}^{\text{Ga}} = 0.233 \text{ MeV} \implies pp, {}^7\text{Be}, {}^8\text{B}, pep, hep, {}^{13}\text{N}, {}^{15}\text{O}, {}^{17}\text{F}$

$$\text{SAGE+GALLEX+GNO} \implies \frac{R_{\text{Ga}}^{\text{exp}}}{R_{\text{Ga}}^{\text{SSM}}} = 0.56 \pm 0.03$$

$$R_{\text{Ga}}^{\text{exp}} = 72.4 \pm 4.7 \text{ SNU}$$

$$R_{\text{Ga}}^{\text{SSM}} = 128_{-7}^{+9} \text{ SNU}$$

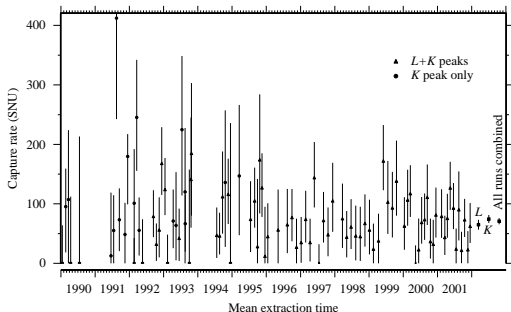
SAGE: Soviet-American Gallium Experiment

Baksan Neutrino Observatory, northern Caucasus

50 tons of metallic ^{71}Ga , 2000 m deep, 4700 m.w.e. $\Rightarrow \Phi_{\mu} \simeq 2.6 \text{ m}^{-2} \text{ day}^{-1}$

detector test: ^{51}Cr Source: $R = 0.95_{-0.10}^{+0.11}_{-0.05}$ [PRC 59 (1999) 2246]

1990 – 2001 $\Rightarrow \frac{R_{\text{Ga}}^{\text{SAGE}}}{R_{\text{Ga}}^{\text{SSM}}} = 0.54 \pm 0.05$ [astro-ph/0204245]



GALLEX: GALLium EXperiment

Gran Sasso Underground Laboratory, Italy, overhead shielding: 3300 m.w.e.

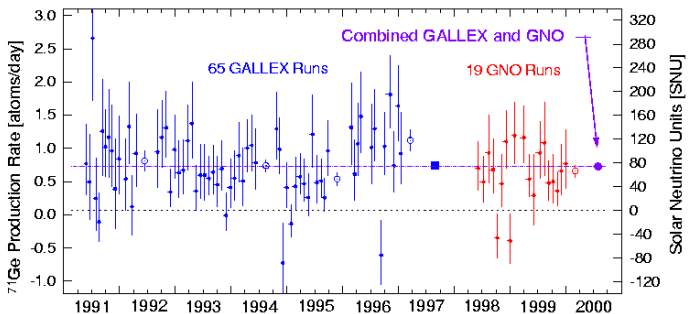
30.3 tons of gallium in 101 tons of gallium chloride ($\text{GaCl}_3\text{-HCl}$) solution

May 1991 – Jan 1997 $\implies \frac{R_{\text{Ga}}^{\text{GALLEX}}}{R_{\text{Ga}}^{\text{SSM}}} = 0.61 \pm 0.06$ [PLB 477 (1999) 127]

GNO: Gallium Neutrino Observatory

continuation of GALLEX: 30.3 tons of gallium

May 1998 – Jan 2000 \Rightarrow $\frac{R_{\text{Ga}}^{\text{GNO}}}{R_{\text{Ga}}^{\text{SSM}}} = 0.51 \pm 0.08$ [PLB 490 (2000) 16]



$$\frac{R_{\text{Ga}}^{\text{GALLEX+GNO}}}{R_{\text{Ga}}^{\text{SSM}}} = 0.58 \pm 0.05$$

Kamiokande

water Cherenkov detector $\nu + e^- \rightarrow \nu + e^-$

Sensitive to ν_e, ν_μ, ν_τ , but $\sigma(\nu_e) \simeq 6\sigma(\nu_{\mu,\tau})$

Kamioka mine (200 km west of Tokyo), 1000 m underground, 2700 m.w.e.

3000 tons of water, 680 tons fiducial volume, 948 PMTs

threshold: $E_{\text{th}}^{\text{Kam}} \simeq 6.75 \text{ MeV} \implies {}^8\text{B}, \text{hep}$

Jan 1987 – Feb 1995 (2079 days)

$$\frac{R_{\nu_e}^{\text{Kam}}}{R_{\nu_e}^{\text{SSM}}} = 0.55 \pm 0.08 \quad [\text{PRL 77 (1996) 1683}]$$

Super-Kamiokande

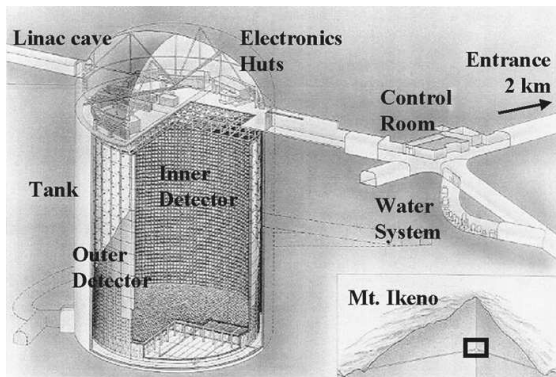
continuation of Kamiokande

50 ktons of water, 22.5 ktons fiducial volume, 11146 PMTs

threshold: $E_{\text{th}}^{\text{Kam}} \simeq 4.75 \text{ MeV} \implies {}^8\text{B}$, *hep*

1996 – 2001 (1496 days)

$$\frac{R_{\nu_e}^{\text{SK}}}{R_{\nu_e}^{\text{SSM}}} = 0.465 \pm 0.015 \quad [\text{SK, PLB 539 (2002) 179}]$$



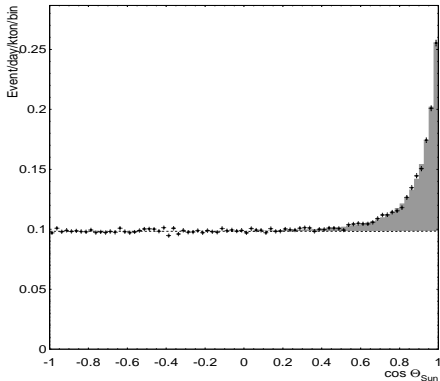
the Super-Kamiokande underground water Cherenkov detector
located near Higashi-Mozumi, Gifu Prefecture, Japan
access is via a 2 km long truck tunnel

[R. J. Wilkes, SK, hep-ex/0212035]

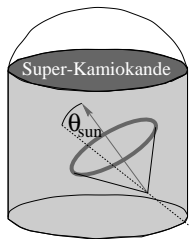
Super-Kamiokande $\cos \theta_{\text{sun}}$ distribution

the points represent observed data, the histogram shows the best-fit signal (shaded) plus background, the horizontal dashed line shows the estimated background

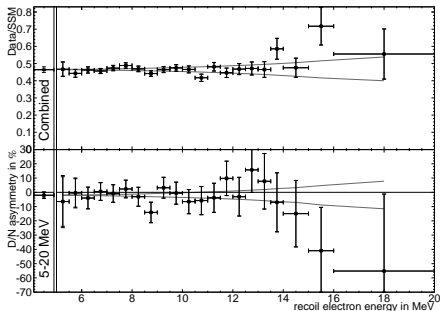
the peak at $\cos \theta_{\text{sun}} = 1$ is due to solar neutrinos



[Smy, hep-ex/0208004]



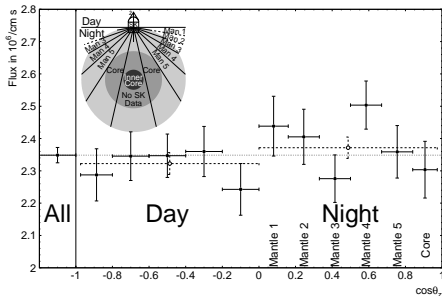
Super-Kamiokande energy spectrum normalized to BP2000 SSM



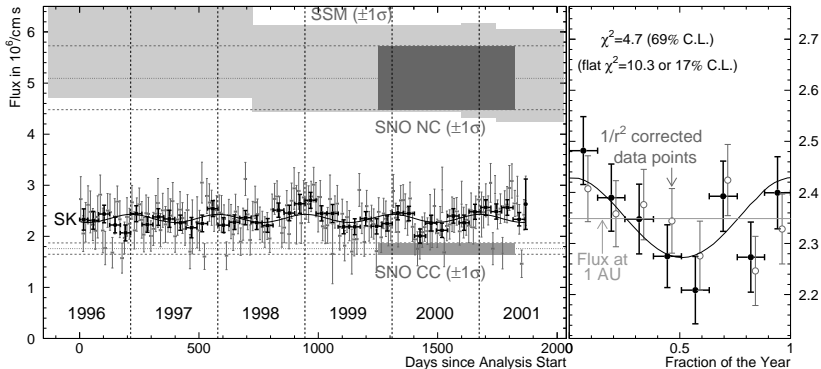
Day-Night asymmetry
as a function of energy

[Smy, hep-ex/0208004]

solar zenith angle (θ_z) dependence of Super-Kamiokande data



Time variation of the Super-Kamiokande data



The gray data points are measured every 10 days.

The black data points are measured every 1.5 months.

The black line indicates the expected annual 7% flux variation.

The right-hand panel combines the 1.5 month bins to search for yearly variations.

The gray data points (open circles) are obtained from the black data points by subtracting the expected 7% variation.

[Smy, hep-ex/0208004]

SNO: Sudbury Neutrino Observatory

water Cherenkov detector, Sudbury, Ontario, Canada

1 kton of D_2O , 9456 20-cm PMTs

2073 m underground, 6010 m.w.e.



$$\left. \begin{array}{l} \text{CC threshold: } E_{\text{th}}^{\text{SNO}}(\text{CC}) \simeq 8.2 \text{ MeV} \\ \text{NC threshold: } E_{\text{th}}^{\text{SNO}}(\text{NC}) \simeq 2.2 \text{ MeV} \\ \text{ES threshold: } E_{\text{th}}^{\text{SNO}}(\text{ES}) \simeq 7.0 \text{ MeV} \end{array} \right\} \Rightarrow {}^8\text{B, hep}$$

D_2O phase: 1999 – 2001

$$\frac{R_{\text{CC}}^{\text{SNO}}}{R_{\text{CC}}^{\text{SSM}}} = 0.35 \pm 0.02$$

$$\frac{R_{\text{NC}}^{\text{SNO}}}{R_{\text{NC}}^{\text{SSM}}} = 1.01 \pm 0.13$$

$$\frac{R_{\text{ES}}^{\text{SNO}}}{R_{\text{ES}}^{\text{SSM}}} = 0.47 \pm 0.05$$

[PRL 89 (2002) 011301]

$NaCl$ phase: 2001 – 2002

$$\frac{R_{\text{CC}}^{\text{SNO}}}{R_{\text{CC}}^{\text{SSM}}} = 0.31 \pm 0.02$$

$$\frac{R_{\text{NC}}^{\text{SNO}}}{R_{\text{NC}}^{\text{SSM}}} = 1.03 \pm 0.09$$

$$\frac{R_{\text{ES}}^{\text{SNO}}}{R_{\text{ES}}^{\text{SSM}}} = 0.44 \pm 0.06$$

[nucl-ex/0309004]

$$\Phi_{\nu_e}^{\text{SNO}} = 1.76 \pm 0.11 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

$$\Phi_{\nu_\mu, \nu_\tau}^{\text{SNO}} = 5.41 \pm 0.66 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

SNO solved
solar neutrino problem



Neutrino Physics
(April 2002)

[SNO, PRL 89 (2002) 011301, nucl-ex/0204008]

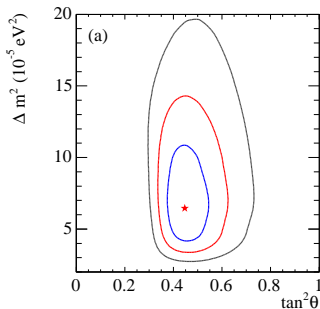
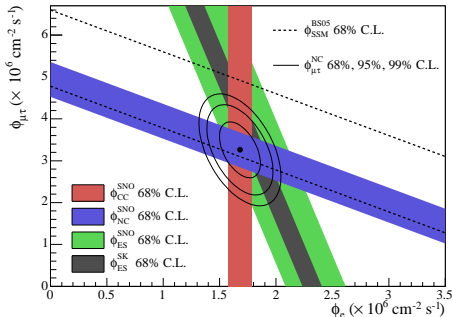
$\nu_e \rightarrow \nu_\mu, \nu_\tau$ oscillations



Large Mixing Angle solution

$$\Delta m^2 \simeq 7 \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \vartheta \simeq 0.45$$



[SNO, PRC 72 (2005) 055502, nucl-ex/0502021]

KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector

long-baseline reactor $\bar{\nu}_e$ experiment

Kamioka mine (200 km west of Tokyo), 1000 m underground, 2700 m.w.e.

53 nuclear power reactors in Japan and Korea

6.7% of flux from one reactor at 88 km

average distance from reactors: 180 km 79% of flux from 26 reactors at 138–214 km

14.3% of flux from other reactors at >295 km

1 kt liquid scintillator detector: $\bar{\nu}_e + p \rightarrow e^+ + n$, energy threshold: $E_{th}^{\bar{\nu}_e p} = 1.8 \text{ MeV}$

data taking: 4 March – 6 October 2002, 145.1 days (162 ton yr)

expected number of reactor neutrino events (no osc.):

$$N_{\text{expected}}^{\text{KamLAND}} = 86.8 \pm 5.6$$

expected number of background events:

$$N_{\text{background}}^{\text{KamLAND}} = 0.95 \pm 0.99$$

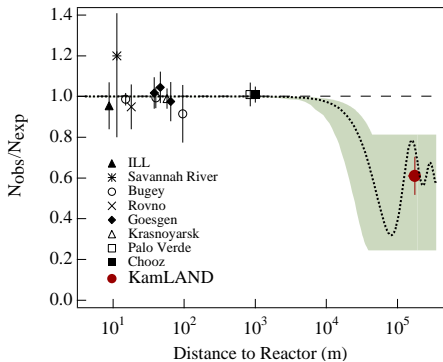
observed number of neutrino events:

$$N_{\text{observed}}^{\text{KamLAND}} = 54$$

$$\frac{N_{\text{observed}}^{\text{KamLAND}} - N_{\text{background}}^{\text{KamLAND}}}{N_{\text{expected}}^{\text{KamLAND}}} = 0.611 \pm 0.085 \pm 0.041$$

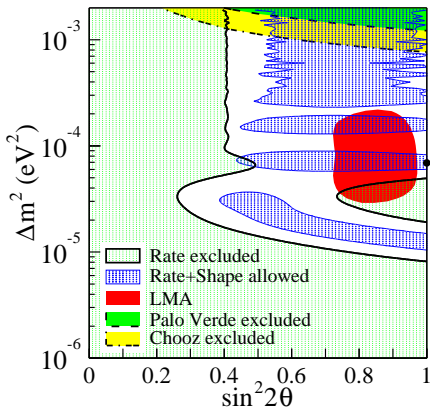
99.95% C.L. evidence
of $\bar{\nu}_e$ disappearance

confirmation of LMA (December 2002)



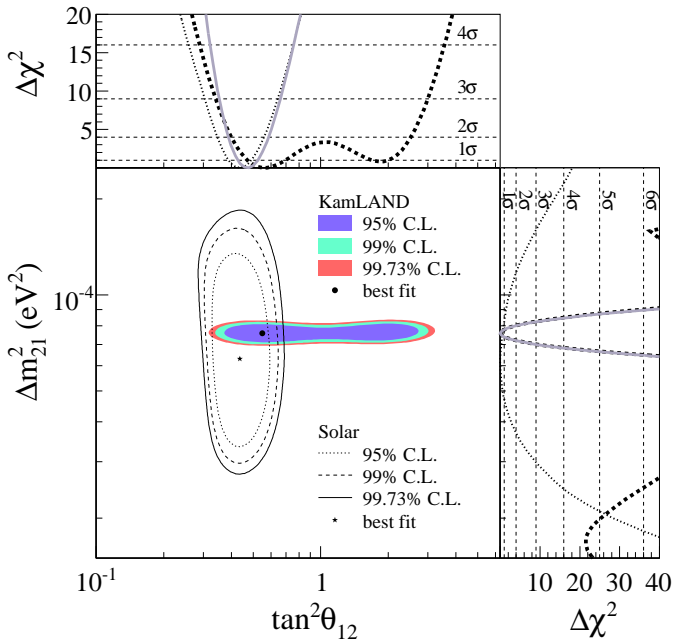
Shade: 95% C.L. LMA

Curve:
$$\begin{cases} \Delta m^2 = 5.5 \times 10^{-5} \text{ eV}^2 \\ \sin^2 2\theta = 0.83 \end{cases}$$

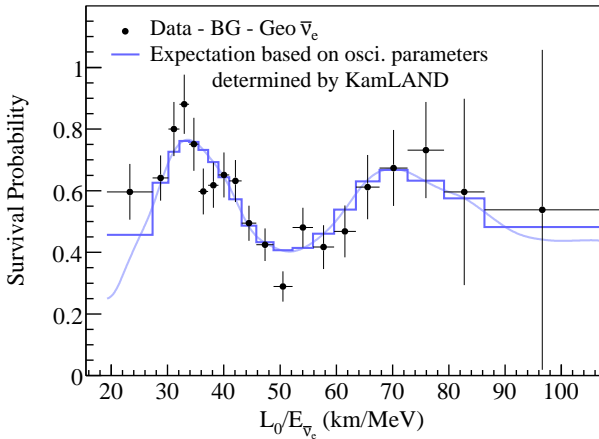


95% C.L.

[KamLAND, PRL 90 (2003) 021802, hep-ex/0212021]

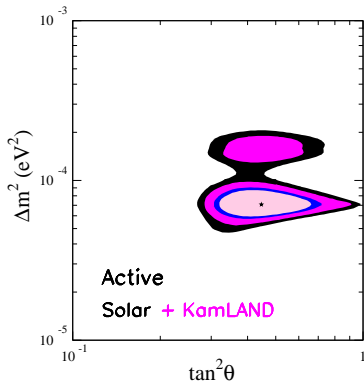


[KamLAND, PRL 100 (2008) 221803]



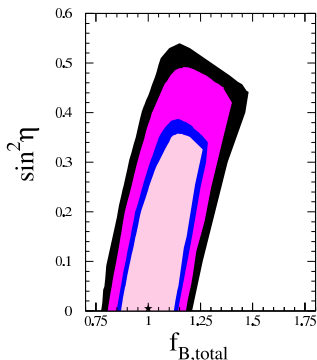
[KamLAND, PRL 100 (2008) 221803]

Sterile Neutrinos in Solar Neutrino Flux?



90%, 95%, 99%, 99.73% (3σ) C.L.

[Bahcall, Gonzalez-Garcia, Pena-Garay, JHEP 0302 (2003) 009]



$$\nu_e \rightarrow \cos \eta \nu_a + \sin \eta \nu_s$$

$$\sin^2 \eta < 0.52 (3\sigma)$$

$$f_{B,\text{total}} = \frac{\Phi_{8B}}{\Phi_{8B}^{\text{SSM}}} = 1.00 \pm 0.06$$

Determination of Solar Neutrino Fluxes

[Bahcall, Peña-Garay, hep-ph/0305159]

fit of solar and KamLAND neutrino data with fluxes as free parameters

+ luminosity constraint

$$\sum_r \alpha_r \Phi_r = K_{\odot} \quad (r = pp, pep, hep, {}^7\text{Be}, {}^8\text{B}, {}^{13}\text{N}, {}^{15}\text{O}, {}^{17}\text{F})$$
$$K_{\odot} \equiv \mathcal{L}_{\odot}/4\pi(1\text{a.u.})^2 = 8.534 \times 10^{11} \text{ MeV cm}^{-2} \text{ s}^{-1}$$

solar constant

$$\Delta m^2 = 7.3_{-0.6}^{+0.4} \text{ eV}^2 \quad \tan^2 \vartheta = 0.42_{-0.06}^{+0.08} \left(\begin{smallmatrix} +0.39 \\ -0.19 \end{smallmatrix} \right)$$

$$\frac{\Phi_{8\text{B}}}{\Phi_{8\text{B}}^{\text{SSM}}} = 1.01_{-0.06}^{+0.06} \left(\begin{smallmatrix} +0.22 \\ -0.17 \end{smallmatrix} \right)$$

moderate uncertainty
will improve with new SNO
NC data (salt phase)

$$\frac{\Phi_{7\text{Be}}}{\Phi_{7\text{Be}}^{\text{SSM}}} = 0.97_{-0.54}^{+0.28} \left(\begin{smallmatrix} +0.85 \\ -0.97 \end{smallmatrix} \right)$$

large uncertainty
needs ${}^7\text{Be}$ experiment
(KamLAND, Borexino?)

$$\frac{\Phi_{pp}}{\Phi_{pp}^{\text{SSM}}} = 1.02_{-0.02}^{+0.02} \left(\begin{smallmatrix} +0.07 \\ -0.07 \end{smallmatrix} \right)$$

small uncertainty

$$\text{CNO luminosity: } \mathcal{L}_{\text{CNO}}/\mathcal{L}_{\odot} = 0.0_{-0.0}^{+2.8} \left(\begin{smallmatrix} +7.3 \\ -0.0 \end{smallmatrix} \right)$$

[Bahcall, Gonzalez-Garcia, Peña-Garay, PRL 90 (2003) 131301]

Details of Solar Neutrino Oscillations

best fit of reactor + solar neutrino data: $\Delta m^2 \simeq 7 \times 10^{-5} \text{ eV}^2$ $\tan^2 \vartheta \simeq 0.4$

$$\overline{P}_{\nu_e \rightarrow \nu_e}^{\text{sun}} = \frac{1}{2} + \left(\frac{1}{2} - P_c \right) \cos 2\vartheta_M^0 \cos 2\vartheta$$

$$P_c = \frac{\exp\left(-\frac{\pi}{2}\gamma F\right) - \exp\left(-\frac{\pi}{2}\gamma \frac{F}{\sin^2 \vartheta}\right)}{1 - \exp\left(-\frac{\pi}{2}\gamma \frac{F}{\sin^2 \vartheta}\right)} \quad \gamma = \frac{\Delta m^2 \sin^2 2\vartheta}{2E \cos 2\vartheta \left| \frac{d \ln A}{dx} \right|_R} \quad F = 1 - \tan^2 \vartheta$$

$$A_{\text{CC}} \simeq 2\sqrt{2}EG_F N_e^c \exp\left(-\frac{x}{x_0}\right) \implies \left| \frac{d \ln A}{dx} \right| \simeq \frac{1}{x_0} = \frac{10.54}{R_\odot} \simeq 3 \times 10^{-15} \text{ eV}$$

$$\tan^2 \vartheta \simeq 0.4 \implies \sin^2 2\vartheta \simeq 0.82, \cos 2\vartheta \simeq 0.43 \quad \gamma \simeq 2 \times 10^4 \left(\frac{E}{\text{MeV}} \right)^{-1}$$

$$\gamma \gg 1 \implies P_c \ll 1 \implies \overline{P}_{\nu_e \rightarrow \nu_e}^{\text{sun,LMA}} \simeq \frac{1}{2} + \frac{1}{2} \cos 2\vartheta_M^0 \cos 2\vartheta$$

$$\cos 2\vartheta_M^0 = \frac{\Delta m^2 \cos 2\vartheta - A_{CC}^0}{\sqrt{(\Delta m^2 \cos 2\vartheta - A_{CC}^0)^2 + (\Delta m^2 \sin 2\vartheta)^2}}$$

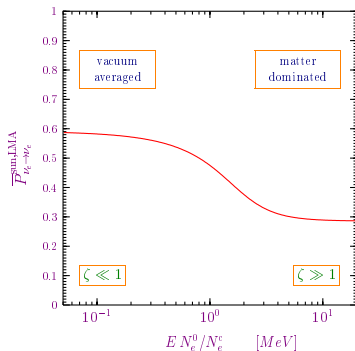
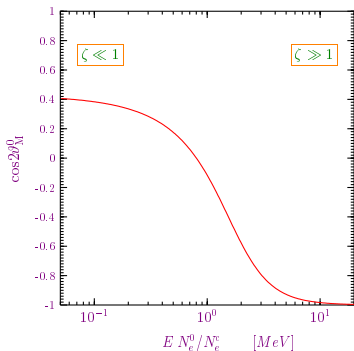
critical parameter [Bahcall, Peña-Garay, hep-ph/0305159]

$$\zeta = \frac{A_{CC}^0}{\Delta m^2 \cos 2\vartheta} = \frac{2\sqrt{2}EG_F N_e^0}{\Delta m^2 \cos 2\vartheta} \simeq 1.2 \left(\frac{E}{\text{MeV}} \right) \left(\frac{N_e^0}{N_e^c} \right)$$

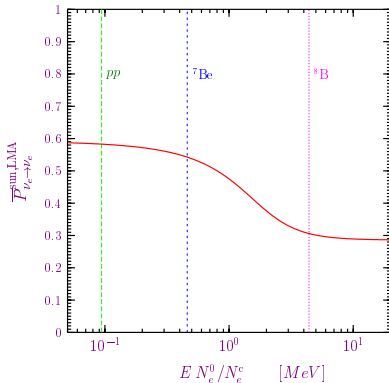
$$\zeta \ll 1 \implies \vartheta_M^0 \simeq \vartheta \implies \overline{P}_{\nu_e \rightarrow \nu_e}^{\text{sun}} \simeq 1 - \frac{1}{2} \sin^2 2\vartheta$$

vacuum averaged
survival probability
matter dominated
survival probability

$$\zeta \gg 1 \implies \vartheta_M^0 \simeq \pi/2 \implies \overline{P}_{\nu_e \rightarrow \nu_e}^{\text{sun}} \simeq \sin^2 \vartheta$$



$$\begin{aligned} \langle E \rangle_{pp} &\simeq 0.27 \text{ MeV}, \quad \langle r_0 \rangle_{pp} \simeq 0.1 R_{\odot} &\implies &\langle E N_e^0 / N_e^c \rangle_{pp} \simeq 0.094 \text{ MeV} \\ E_{7\text{Be}} &\simeq 0.86 \text{ MeV}, \quad \langle r_0 \rangle_{7\text{Be}} \simeq 0.06 R_{\odot} &\implies &\langle E N_e^0 / N_e^c \rangle_{7\text{Be}} \simeq 0.46 \text{ MeV} \\ \langle E \rangle_{8\text{B}} &\simeq 6.7 \text{ MeV}, \quad \langle r_0 \rangle_{8\text{B}} \simeq 0.04 R_{\odot} &\implies &\langle E N_e^0 / N_e^c \rangle_{8\text{B}} \simeq 4.4 \text{ MeV} \end{aligned}$$



each neutrino experiment is mainly sensitive to one flux
 each neutrino experiment is mainly sensitive to ϑ
 accurate pp experiment can improve determination of ϑ

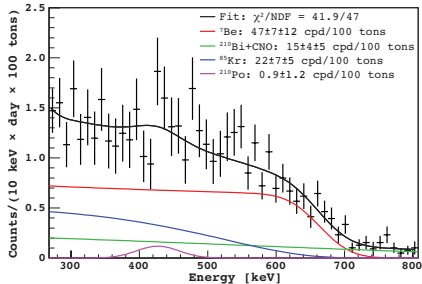
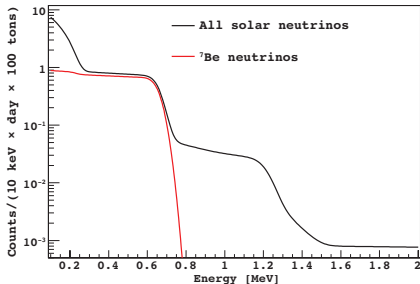
[Bahcall, Peña-Garay, hep-ph/0305159]

BOREXino

[BOREXino, arXiv:0708.2251]

Real-time measurement of ${}^7\text{Be}$ solar neutrinos (0.862 MeV)

$$\nu + e \rightarrow \nu + e \quad E = 0.862 \text{ MeV} \quad \Rightarrow \quad \sigma_{\nu e} \simeq 5.5 \sigma_{\nu\mu, \nu\tau}$$



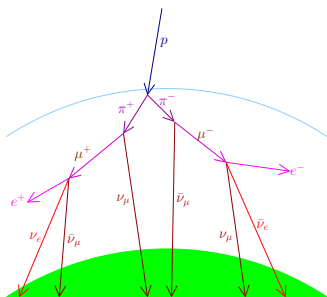
$$n_{\text{the}}^{\text{no-osc}} = 75 \pm 4 \text{ day}^{-1} (100 \text{ tons})^{-1} \quad n_{\text{exp}} = 47 \pm 7 \pm 12 \text{ day}^{-1} (100 \text{ tons})^{-1}$$

$$n_{\text{the}}^{\text{osc}} = 49 \pm 4 \text{ day}^{-1} (100 \text{ tons})^{-1} \quad (n_{\text{the}}^{\text{no-osc}} - n_{\text{exp}}) / \Delta n \simeq 1.9$$

Atmospheric and LBL Oscillation Experiments

- Solar Neutrinos and KamLAND
- Atmospheric and LBL Oscillation Experiments
 - Atmospheric Neutrinos
 - Super-Kamiokande Up-Down Asymmetry
 - Fit of Super-Kamiokande Atmospheric Data
 - Kamiokande, Soudan-2, MACRO and MINOS
 - K2K
 - MINOS
 - Sterile Neutrinos in Atmospheric Neutrino Flux?
- Phenomenology of Three-Neutrino Mixing
- Absolute Scale of Neutrino Masses
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Atmospheric Neutrinos



$$\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \simeq 2 \quad \text{at } E \lesssim 1 \text{ GeV}$$

uncertainty on ratios: $\sim 5\%$

uncertainty on fluxes: $\sim 30\%$

ratio of ratios

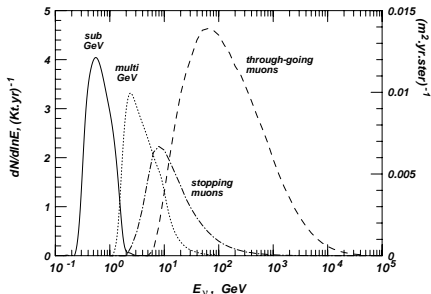
$$R \equiv \frac{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{data}}}{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{MC}}}$$

$$R_{\text{sub-GeV}}^{\text{K}} = 0.60 \pm 0.07 \pm 0.05$$

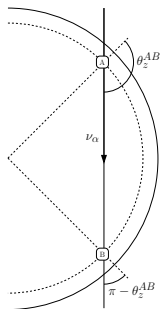
[Kamiokande, PLB 280 (1992) 146]

$$R_{\text{multi-GeV}}^{\text{K}} = 0.57 \pm 0.08 \pm 0.07$$

[Kamiokande, PLB 335 (1994) 237]



Super-Kamiokande Up-Down Asymmetry



$E_\nu \gtrsim 1 \text{ GeV} \Rightarrow$ isotropic flux of cosmic rays

$$\phi_{\nu_\alpha}^{(A)}(\theta_z^{AB}) = \phi_{\nu_\alpha}^{(B)}(\pi - \theta_z^{AB}) \quad \phi_{\nu_\alpha}^{(A)}(\theta_z^{AB}) = \phi_{\nu_\alpha}^{(B)}(\theta_z^{AB})$$

↓

$$\phi_{\nu_\alpha}^{(A)}(\theta_z) = \phi_{\nu_\alpha}^{(A)}(\pi - \theta_z)$$

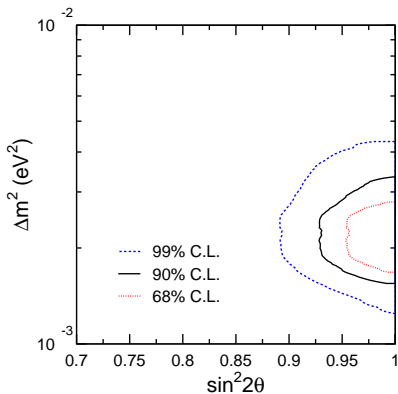
(December 1998)

$$A_{\nu_\mu}^{\text{up-down}}(\text{SK}) = \left(\frac{N_{\nu_\mu}^{\text{up}} - N_{\nu_\mu}^{\text{down}}}{N_{\nu_\mu}^{\text{up}} + N_{\nu_\mu}^{\text{down}}} \right) = -0.296 \pm 0.048 \pm 0.01$$

[Super-Kamiokande, Phys. Rev. Lett. 81 (1998) 1562, hep-ex/9807003]

6 σ MODEL INDEPENDENT EVIDENCE OF ν_μ DISAPPEARANCE!

Fit of Super-Kamiokande Atmospheric Data



Best Fit: $\left\{ \begin{array}{l} \nu_\mu \rightarrow \nu_\tau \\ \Delta m^2 = 2.1 \times 10^{-3} \text{ eV}^2 \\ \sin^2 2\theta = 1.0 \end{array} \right.$

1489.2 live-days (Apr 1996 – Jul 2001)

[Super-Kamiokande, PRD 71 (2005) 112005, hep-ex/0501064]

Measure of ν_τ CC Int. is Difficult:

- ▶ $E_{\text{th}} = 3.5 \text{ GeV} \Rightarrow \sim 20 \text{ events/yr}$
- ▶ τ -Decay \Rightarrow Many Final States

ν_τ -Enriched Sample

$$N_{\nu_\tau}^{\text{the}} = 78 \pm 26 @ \Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$$

$$N_{\nu_\tau}^{\text{exp}} = 138_{-58}^{+50}$$

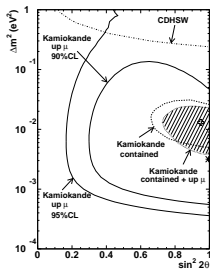
$$N_{\nu_\tau} > 0 @ 2.4\sigma$$

[Super-Kamiokande, PRL 97(2006) 171801, hep-ex/0607059]

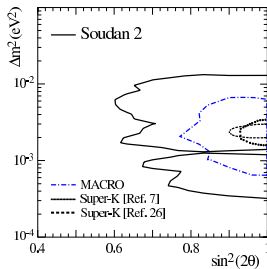
Check: OPERA ($\nu_\mu \rightarrow \nu_\tau$)
CERN to Gran Sasso (CNCS)
 $L \simeq 732 \text{ km}$ $\langle E \rangle \simeq 18 \text{ GeV}$

[NJP 8 (2006) 303, hep-ex/0611023]

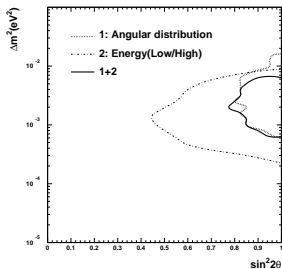
Kamiokande, Soudan-2, MACRO and MINOS



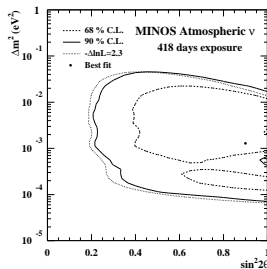
[Kamiokande, hep-ex/9806038]



[Soudan 2, hep-ex/0507068]



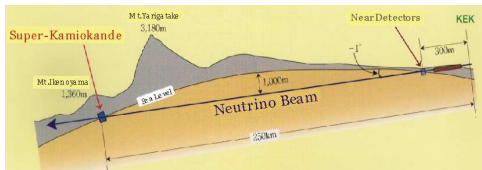
[MACRO, hep-ex/0304037]



[MINOS, hep-ex/0512036]

K2K

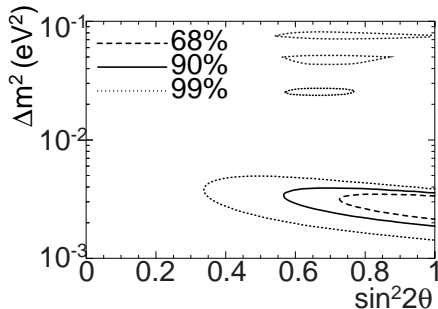
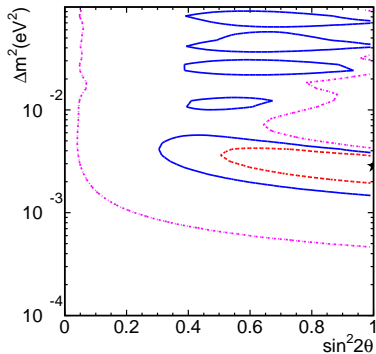
confirmation of atmospheric allowed region (June 2002)



KEK to Kamioka
(Super-Kamiokande)

250 km

$\nu_\mu \rightarrow \nu_\mu$



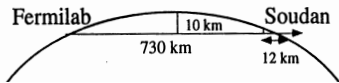
[K2K, PRL 94 (2005) 081802, hep-ex/0411038]

[K2K, Phys. Rev. Lett. 90 (2003) 041801]

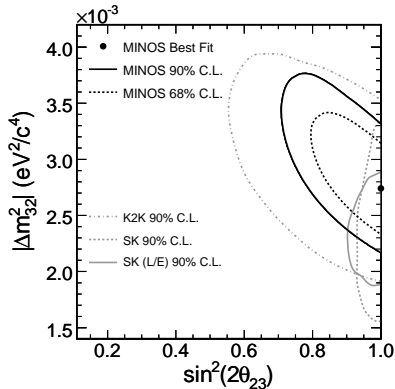
MINOS

May 2005 – Feb 2006

<http://www-nu.fermi.fnal.gov/>



Near Detector: 1 km

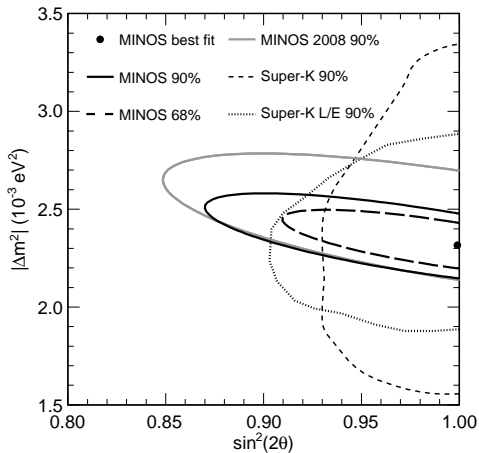


$\nu_\mu \rightarrow \nu_\mu$

$$\Delta m^2 = 2.74^{+0.44}_{-0.26} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta > 0.87 @ 68\% CL$$

[MINOS, PRL 97 (2006) 191801, hep-ex/0607088]



$$|\Delta m_{31}^2| = \left(2.32^{+0.12}_{-0.08}\right) \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{23} > 0.90 \quad (90\% \text{ C.L.})$$

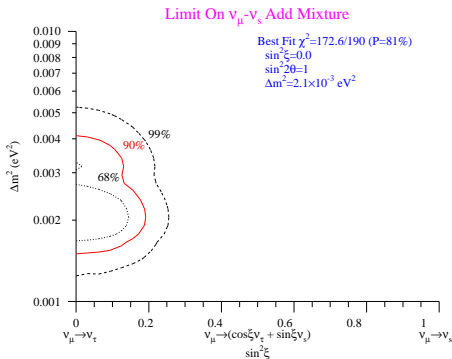
[arXiv:1103.0340v1]

Sterile Neutrinos in Atmospheric Neutrino Flux?

Nature of atmospheric Oscillation

Mode	Best fit	$\Delta\chi^2$	σ
$\nu_\mu\text{-}\nu_\tau$	$\sin^2 2\theta=1.00; \Delta m^2=2.5 \times 10^{-3} \text{eV}^2$	0.0	0.0
$\nu_\mu\text{-}\nu_e$	$\sin^2 2\theta=0.97; \Delta m^2=5.0 \times 10^{-3} \text{eV}^2$	79.3	8.9
$\nu_\mu\text{-}\nu_s$	$\sin^2 2\theta=0.96; \Delta m^2=3.6 \times 10^{-3} \text{eV}^2$	19.0	4.4
LxE	$\sin^2 2\theta=0.90; \alpha=5.3 \times 10^{-4}$	67.1	8.2
ν_μ Decay	$\cos^2 \theta=0.47; \alpha=3.0 \times 10^{-3} \text{eV}^2$	81.1	9.0
ν_μ Decay to ν_s	$\cos^2 \theta=0.33; \alpha=1.1 \times 10^{-2} \text{eV}^2$	14.1	3.8

[Smy (SK), Moriond 2002]

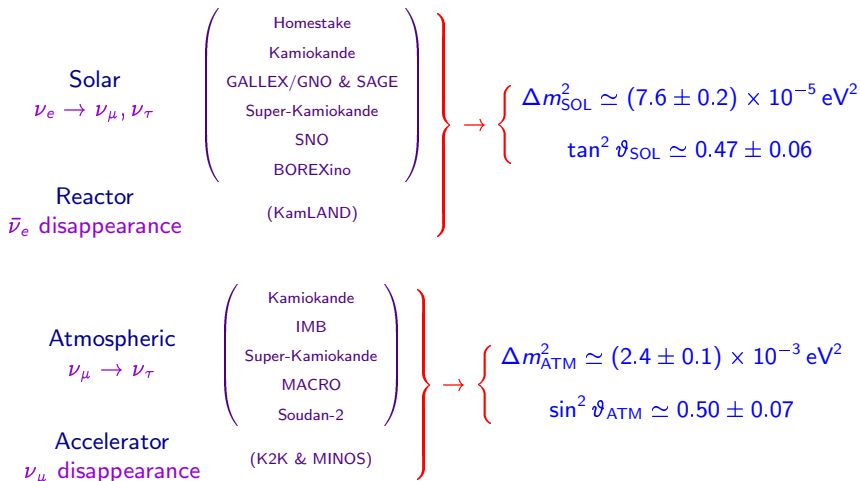


[Nakaya (SK), hep-ex/0209036]

Phenomenology of Three-Neutrino Mixing

- Solar Neutrinos and KamLAND
- Atmospheric and LBL Oscillation Experiments
- Phenomenology of Three-Neutrino Mixing
 - Experimental Evidences of Neutrino Oscillations
 - Three-Neutrino Mixing
- Absolute Scale of Neutrino Masses
- Anomalies Beyond Three-Neutrino Mixing
- Conclusions

Experimental Evidences of Neutrino Oscillations



Two scales of Δm^2 : $\Delta m_{\text{ATM}}^2 \simeq 30 \Delta m_{\text{SOL}}^2$

Large mixings: $\vartheta_{\text{ATM}} \simeq 45^\circ$, $\vartheta_{\text{SOL}} \simeq 34^\circ$

Three-Neutrino Mixing

$$\nu_{\alpha L} = \sum_{k=1}^3 U_{\alpha k} \nu_{kL} \quad (\alpha = e, \mu, \tau)$$

three flavor fields: ν_e, ν_μ, ν_τ

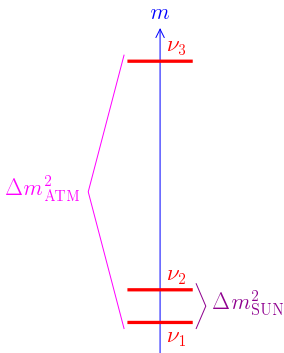
three massive fields: ν_1, ν_2, ν_3

$$\Delta m_{21}^2 + \Delta m_{32}^2 + \Delta m_{13}^2 = m_2^2 - m_1^2 + m_3^2 - m_2^2 + m_1^2 - m_3^2 = 0$$

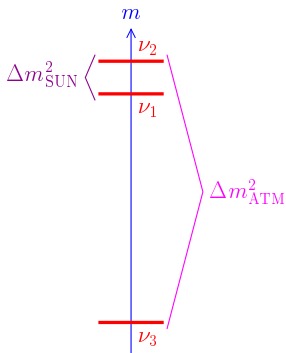
$$\Delta m_{\text{SOL}}^2 = \Delta m_{21}^2 \simeq (7.6 \pm 0.2) \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{\text{ATM}}^2 \simeq |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq (2.4 \pm 0.1) \times 10^{-3} \text{ eV}^2$$

Allowed Three-Neutrino Schemes



"normal"



"inverted"

different signs of $\Delta m_{31}^2 \simeq \Delta m_{32}^2$

absolute scale is not determined by neutrino oscillation data

Mixing Matrix

$$\Delta m_{21}^2 \ll |\Delta m_{31}^2|$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

SOL →
↑
 ATM & LBL

$$\text{CHOOZ: } \begin{cases} \Delta m_{\text{CHOOZ}}^2 = \Delta m_{31}^2 = \Delta m_{\text{ATM}}^2 \\ \sin^2 2\vartheta_{\text{CHOOZ}} = 4|U_{e3}|^2(1 - |U_{e3}|^2) \end{cases}$$

$$|U_{e3}|^2 \lesssim 5 \times 10^{-2}$$

[Bilenky, Giunti, PLB 444 (1998) 379]

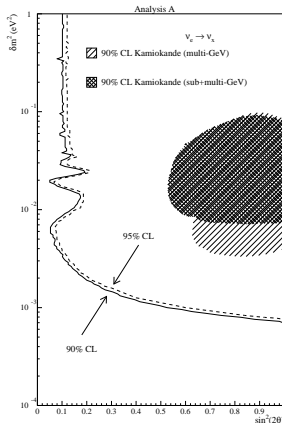
SOLAR AND ATMOSPHERIC ν OSCILLATIONS
ARE PRACTICALLY DECOUPLED!

$$|U_{e1}|^2 \simeq \cos^2 \vartheta_{\text{SOL}}$$

$$|U_{e2}|^2 \simeq \sin^2 \vartheta_{\text{SOL}}$$

$$|U_{\mu 3}|^2 \simeq \sin^2 \vartheta_{\text{ATM}}$$

$$|U_{\tau 3}|^2 \simeq \cos^2 \vartheta_{\text{ATM}}$$



[CHOOZ, PLB 466 (1999) 415]

[Palo Verde, PRD 64 (2001) 112001]

Effective ATM and LBL Oscillation Probability in Vacuum

$$\begin{aligned}
 P_{\nu_\alpha \rightarrow \nu_\beta} &= \left| \sum_{k=1}^3 U_{\alpha k}^* U_{\beta k} e^{-iE_k t} \right|^2 * \left| e^{iE_1 t} \right|^2 \\
 &= \left| \sum_{k=1}^3 U_{\alpha k}^* U_{\beta k} e^{-i(E_k - E_1)t} \right|^2 \rightarrow \left| \sum_{k=1}^3 U_{\alpha k}^* U_{\beta k} \exp\left(\frac{\Delta m_{k1}^2 L}{2E}\right) \right|^2
 \end{aligned}$$

$$E_k \simeq E + \frac{m_k^2}{2E} \quad \frac{\Delta m_{21}^2 L}{2E} \ll 1 \quad \Delta m_{31}^2 \rightarrow \Delta m^2$$

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \left| U_{\alpha 1}^* U_{\beta 1} + U_{\alpha 2}^* U_{\beta 2} + U_{\alpha 3}^* U_{\beta 3} \exp\left(\frac{\Delta m^2 L}{2E}\right) \right|^2$$

$$U_{\alpha 1}^* U_{\beta 1} + U_{\alpha 2}^* U_{\beta 2} = \delta_{\alpha\beta} - U_{\alpha 3}^* U_{\beta 3}$$

$$\begin{aligned}
P_{\nu_\alpha \rightarrow \nu_\beta} &= \left| \delta_{\alpha\beta} - U_{\alpha 3}^* U_{\beta 3} \left[1 - \exp\left(\frac{\Delta m^2 L}{2E}\right) \right] \right|^2 \\
&= \delta_{\alpha\beta} + |U_{\alpha 3}|^2 |U_{\beta 3}|^2 \left(2 - 2 \cos \frac{\Delta m^2 L}{2E} \right) \\
&\quad - 2\delta_{\alpha\beta} |U_{\alpha 3}|^2 \left(1 - \cos \frac{\Delta m^2 L}{2E} \right) \\
&= \delta_{\alpha\beta} - 2|U_{\alpha 3}|^2 \left(\delta_{\alpha\beta} - |U_{\beta 3}|^2 \right) \left(1 - \cos \frac{\Delta m^2 L}{2E} \right) \\
&= \delta_{\alpha\beta} - 4|U_{\alpha 3}|^2 \left(\delta_{\alpha\beta} - |U_{\beta 3}|^2 \right) \sin^2 \frac{\Delta m^2 L}{4E}
\end{aligned}$$

$$\alpha \neq \beta \implies P_{\nu_\alpha \rightarrow \nu_\beta} = 4|U_{\alpha 3}|^2 |U_{\beta 3}|^2 \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$\alpha = \beta \implies P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - 4|U_{\alpha 3}|^2 \left(1 - |U_{\alpha 3}|^2 \right) \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m^2 L}{4E} \right) \quad (\alpha \neq \beta)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 3}|^2|U_{\beta 3}|^2$$

$$P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 3}|^2 (1 - |U_{\alpha 3}|^2)$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

↑
LBL

$$\sin^2 2\vartheta_{ee} \ll 1$$



$$|U_{e3}|^2 \simeq \frac{\sin^2 2\vartheta_{ee}}{4}$$

- ▶ ν_e disappearance experiments:

$$\sin^2 2\vartheta_{ee} = 4|U_{e3}|^2 (1 - |U_{e3}|^2) \simeq 4|U_{e3}|^2$$

- ▶ ν_μ disappearance experiments:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu3}|^2 (1 - |U_{\mu3}|^2)$$

$$|U_{\mu3}|^2 = \frac{1}{2} \left(1 \pm \sqrt{1 - \sin^2 2\vartheta_{\mu\mu}} \right)$$

- ▶ $\nu_\mu \rightarrow \nu_e$ experiments:

$$\sin^2 2\vartheta_{\mu e} = 4|U_{e3}|^2 |U_{\mu3}|^2$$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\vartheta_{23} \simeq \vartheta_{\text{ATM}}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix}}_{\vartheta_{12} \simeq \vartheta_{\text{SOL}}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\beta\beta_{0\nu}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$$\Delta m_{21}^2 = \left(7.65_{-0.20}^{+0.23}\right) \times 10^{-5} \text{ eV}^2 \quad |\Delta m_{31}^2| = \left(2.40_{-0.11}^{+0.12}\right) \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \vartheta_{12} = 0.304_{-0.016}^{+0.022} \quad \sin^2 \vartheta_{23} = 0.50_{-0.06}^{+0.07}$$

$$\sin^2 \vartheta_{13} < 0.035 \quad (90\% \text{ C.L.})$$

[Schwetz, Tortola, Valle, arXiv:0808.2016v3, 11 Feb 2010]

Current Research

measure $\vartheta_{13} \neq 0 \implies$ CP violation, matter effects, mass hierarchy

Bilarge Mixing

$$|U_{e3}|^2 \ll 1$$

$$U \simeq \begin{pmatrix} c_{\vartheta_S} & s_{\vartheta_S} & 0 \\ -s_{\vartheta_S} c_{\vartheta_A} & c_{\vartheta_S} c_{\vartheta_A} & s_{\vartheta_A} \\ s_{\vartheta_S} s_{\vartheta_A} & -c_{\vartheta_S} s_{\vartheta_A} & c_{\vartheta_A} \end{pmatrix} \Rightarrow \begin{cases} \nu_e = c_{\vartheta_S} \nu_1 + s_{\vartheta_S} \nu_2 \\ \nu_a^{(S)} = -s_{\vartheta_S} \nu_1 + c_{\vartheta_S} \nu_2 \\ \phantom{\nu_a^{(S)}} = c_{\vartheta_A} \nu_\mu - s_{\vartheta_A} \nu_\tau \end{cases}$$

$$\sin^2 2\vartheta_A \simeq 1 \Rightarrow \vartheta_A \simeq \frac{\pi}{4} \Rightarrow U \simeq \begin{pmatrix} c_{\vartheta_S} & s_{\vartheta_S} & 0 \\ -s_{\vartheta_S}/\sqrt{2} & c_{\vartheta_S}/\sqrt{2} & 1/\sqrt{2} \\ s_{\vartheta_S}/\sqrt{2} & -c_{\vartheta_S}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

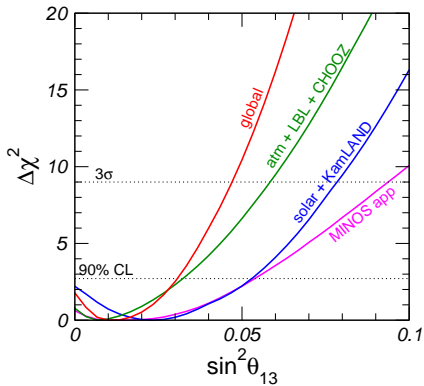
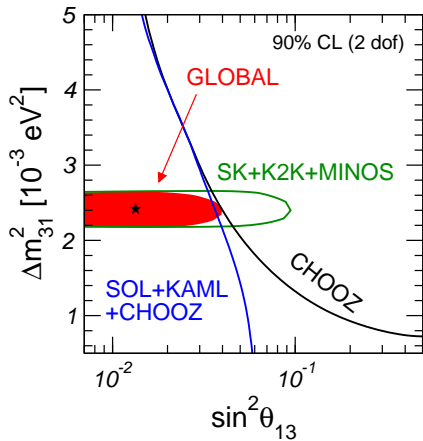
$$\text{Solar } \nu_e \rightarrow \nu_a^{(S)} \simeq \frac{1}{\sqrt{2}} (\nu_\mu - \nu_\tau)$$

$$\frac{\Phi_{CC}^{\text{SNO}}}{\Phi_{\nu_e}^{\text{SSM}}} \simeq \frac{1}{3} \Rightarrow \Phi_{\nu_e} \simeq \Phi_{\nu_\mu} \simeq \Phi_{\nu_\tau} \text{ for } E \gtrsim 6 \text{ MeV}$$

$$\sin^2 \vartheta_S \simeq \frac{1}{3} \Rightarrow U \simeq \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Tri-Bimaximal Mixing

[Harrison, Perkins, Scott, hep-ph/0202074]

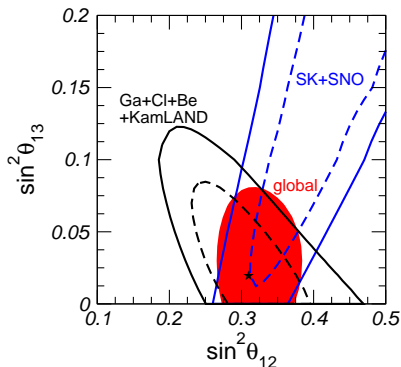
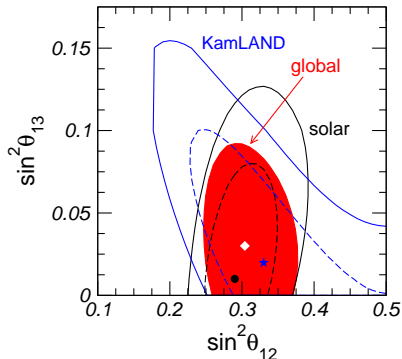


[Mezzetto, Schwetz, arXiv:1003.5800, 10 Aug 2010]

Hint of $\vartheta_{13} > 0$

[Fogli, Lisi, Marrone, Palazzo, Rotunno, NO-VE, April 2008] [Balantekin, Yilmaz, JPG 35 (2008) 075007]

$\sin^2 \vartheta_{13} = 0.016 \pm 0.010$ [Fogli, Lisi, Marrone, Palazzo, Rotunno, PRL 101 (2008) 141801]

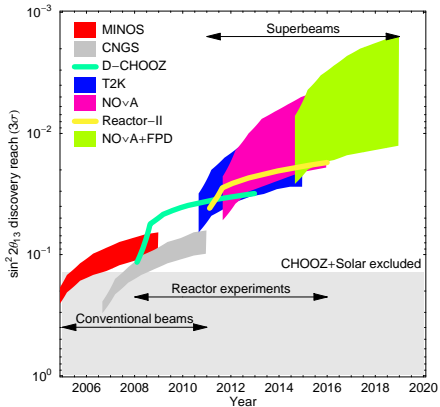


[Schwetz, Tortola, Valle, arXiv:0808.2016v3, 11 Feb 2010]

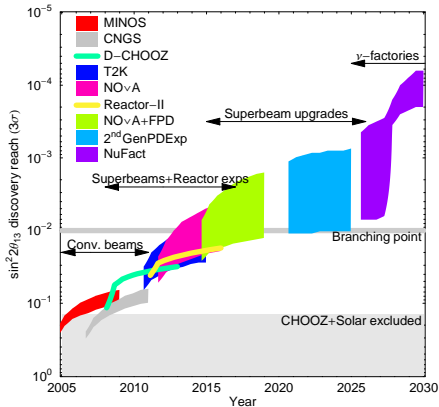
[Mezzetto, Schwetz, arXiv:1003.5800, 10 Aug 2010]

$$P_{\nu_e \rightarrow \nu_e}^{(-)} \simeq \begin{cases} (1 - \sin^2 \vartheta_{13})^2 (1 - 0.5 \sin^2 \vartheta_{12}) & \text{SOL low-energy \& KamLAND} \\ (1 - \sin^2 \vartheta_{13})^2 \sin^2 \vartheta_{12} & \text{SOL high-energy (matter effect)} \end{cases}$$

The Hunt for ϑ_{13}



3σ sensitivities. Bands reflect dependence of sensitivity on the CP violating phase δ_{13} .



“Branching point” refers to the decision between an upgraded superbeam and/or detector and a neutrino factory program. Neutrino factory is assumed to switch polarity after 2.5 years.

[Physics at a Fermilab Proton Driver, Albrow et al, hep-ex/0509019]

Effective LBL Oscillation Probabilities

$$\Delta = \frac{\Delta m_{31}^2 L}{4E} \quad \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \quad A = \frac{2EV}{\Delta m_{31}^2 L} \quad V = \sqrt{2}G_F N_e$$

$$\sin \theta_{13} \ll 1 \quad \alpha \ll 1$$

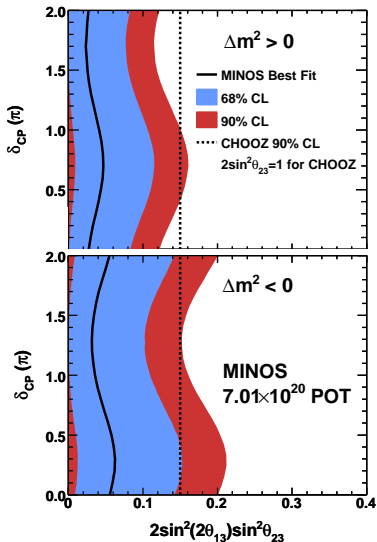
$$P_{\nu_e \rightarrow \nu_e}^{\text{LBL}} \simeq 1 - \sin^2 2\vartheta_{13} \sin^2 \Delta - \alpha^2 \Delta^2 \sin^2 2\vartheta_{12}$$

$$P_{\nu_\mu \rightarrow \nu_e}^{\text{LBL}} \simeq \sin^2 2\vartheta_{13} \sin^2 \vartheta_{23} \frac{\sin^2[(1-A)\Delta]}{(1-A)^2} \\ + \alpha \sin 2\vartheta_{13} \sin 2\vartheta_{12} \sin 2\vartheta_{23} \cos(\Delta + \delta_{13}) \frac{\sin(A\Delta)}{A} \frac{\sin[(1-A)\Delta]}{1-A} \\ + \alpha^2 \sin^2 2\vartheta_{12} \cos^2 \vartheta_{23} \frac{\sin^2(A\Delta)}{A^2}$$

[Mezzetto, Schwetz, arXiv:1003.5800]

MINOS

[arXiv:1006.0996v1]



54 ν_e events in FD

background: $49.1 \pm 7.0 \pm 2.7$

0.7 σ excess

if $\delta_{13} = 0$

$$2 \sin^2 2\vartheta_{13} \sin^2 \vartheta_{23} < \begin{cases} 0.12 & \text{(NH)} \\ 0.20 & \text{(IH)} \end{cases}$$

(90% C.L.)

CP Violation

$$P_{\nu_\alpha \rightarrow \nu_\beta} - P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta} = -16 J_{\alpha\beta} \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

$$J_{\alpha\beta} = \text{Im}(U_{\alpha 1} U_{\alpha 2}^* U_{\beta 1}^* U_{\beta 2}) = \pm J$$

$$J = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin \delta_{13}$$

Necessary conditions for observation of CP violation:

- ▶ Sensitivity to small ϑ_{13}
- ▶ Sensitivity to oscillations due to Δm_{21}^2 and Δm_{31}^2

Mass Hierarchy

► $\nu_e \leftrightarrow \nu_\mu$ MSW resonance: $\cos 2\vartheta_{13} = \frac{2EV}{\Delta m_{13}^2}$

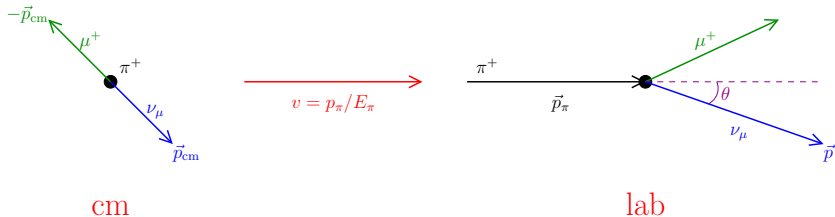
Requires $\Delta m_{13}^2 > 0$

► $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ MSW resonance: $\cos 2\vartheta_{13} = -\frac{2EV}{\Delta m_{13}^2}$

Requires $\Delta m_{13}^2 < 0$

Off-Axis Experiments

high-intensity WB beam
detector shifted by a small angle from axis of beam
almost monochromatic neutrino energy



$$E_{\text{cm}} = p_{\text{cm}} = \frac{m_{\pi}}{2} \left(1 - \frac{m_{\mu}^2}{m_{\pi}^2} \right) \simeq 29.79 \text{ MeV}$$

$$\gamma = (1 - v^2)^{-1/2} = E_{\pi} / m_{\pi} \gg 1$$
$$\begin{cases} E = \gamma (E_{\text{cm}} + v p_{\text{cm}}^z) \\ p^z = \gamma (v E_{\text{cm}} + p_{\text{cm}}^z) \end{cases}$$

$$p^z = p \cos \theta \quad \Rightarrow \quad E = \frac{E_{\text{cm}}}{\gamma (1 - v \cos \theta)}$$

$$\cos \theta \simeq 1 - \theta^2/2 \quad \text{and} \quad v \simeq 1$$

$$E = \frac{E_{\text{cm}}}{\gamma(1 - v \cos \theta)} \simeq \frac{\gamma(1 + v)}{1 + \gamma^2 \theta^2 v(1 + v)/2} E_{\text{cm}} \simeq \frac{2\gamma}{1 + \gamma^2 \theta^2} E_{\text{cm}}$$

$$E \simeq \left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \frac{E_\pi}{1 + \gamma^2 \theta^2} = \left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \frac{E_\pi m_\pi^2}{m_\pi^2 + E_\pi^2 \theta^2}$$

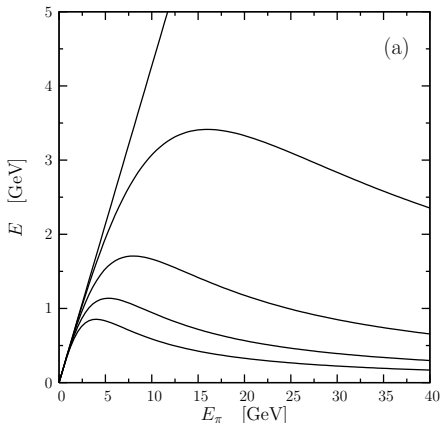
▶ $\theta = 0 \implies E \propto E_\pi$ WB beam

▶ $E_\pi \theta \gg m_\pi \implies E \propto \frac{m_\pi^2}{E_\pi \theta^2}$ high-energy π^+ give low-energy ν_μ

$$\frac{dE}{dE_\pi} \simeq \left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \frac{1 - \gamma^2 \theta^2}{(1 + \gamma^2 \theta^2)^2}$$

$$\frac{dE}{dE_\pi} \simeq 0 \quad \text{for} \quad \theta = \gamma^{-1} = \frac{m_\pi}{E_\pi} \implies E \simeq \left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \frac{m_\pi}{2\theta} \simeq \frac{29.79 \text{ MeV}}{\theta}$$

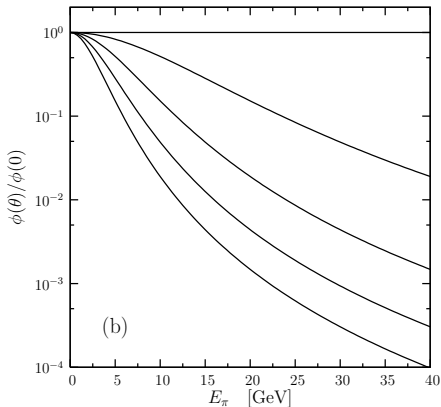
off-axis angle $\theta \simeq m_\pi / \langle E_\pi \rangle \implies E \simeq \frac{29.79 \text{ MeV}}{\theta}$



$\theta = 0.0^\circ, 0.5^\circ, 1.0^\circ, 1.5^\circ, 2.0^\circ$

- ▶ E can be tuned on oscillation peak $E_{\text{peak}} = \Delta m^2 L / 2\pi$
- ▶ small $E \implies$ short $L_{\text{osc}} = \frac{4\pi E}{\Delta m^2} \implies$ sensitivity to small values of Δm^2

$$\frac{\phi(\theta)}{\phi(0)} = \frac{1}{4} \left(\frac{2}{1 + \gamma^2 \theta^2} \right)^2$$



$$\theta = 0.0^\circ, 0.5^\circ, 1.0^\circ, 1.5^\circ, 2.0^\circ$$

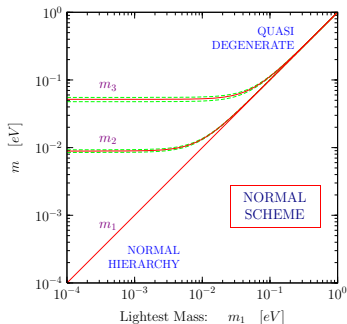
flux suppression requires superbeam

Absolute Scale of Neutrino Masses

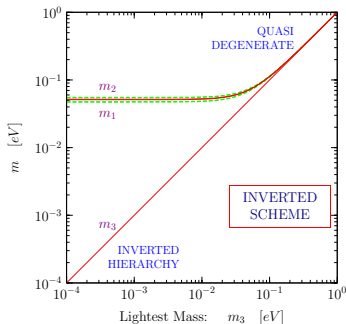
- Solar Neutrinos and KamLAND
- Atmospheric and LBL Oscillation Experiments
- Phenomenology of Three-Neutrino Mixing
- Absolute Scale of Neutrino Masses
 - Mass Hierarchy or Degeneracy?
 - Tritium Beta-Decay
 - Neutrinoless Double-Beta Decay
 - Cosmological Bound on Neutrino Masses
- Anomalies Beyond Three-Neutrino Mixing
- Conclusions

Mass Hierarchy or Degeneracy?

normal scheme



inverted scheme



$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_{\text{SOL}}^2$$

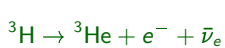
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_{\text{ATM}}^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_{\text{ATM}}^2$$

$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_{\text{ATM}}^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gg \sqrt{\Delta m_{\text{ATM}}^2} \simeq 5 \times 10^{-2} \text{ eV}$

Tritium Beta-Decay

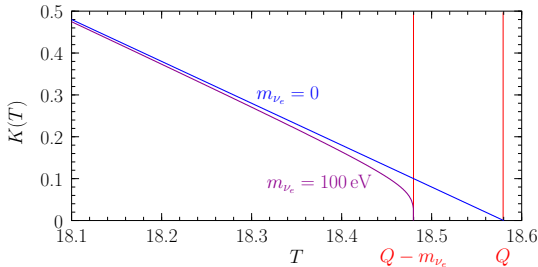


$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) p E (Q - T) \sqrt{(Q - T)^2 - m_{\nu_e}^2}$$

$$Q = M_{{}^3\text{H}} - M_{{}^3\text{He}} - m_e = 18.58 \text{ keV}$$

Kurie plot

$$K(T) = \sqrt{\frac{d\Gamma/dT}{\frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) p E}} = \left[(Q - T) \sqrt{(Q - T)^2 - m_{\nu_e}^2} \right]^{1/2}$$



$$m_{\nu_e} < 2.2 \text{ eV} \quad (95\% \text{ C.L.})$$

Mainz & Troitsk

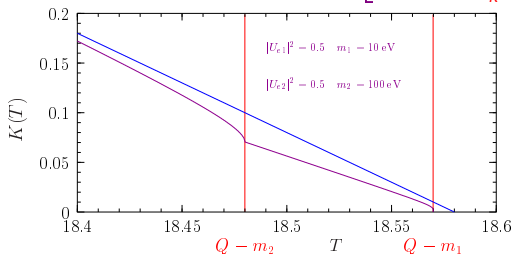
[Weinheimer, hep-ex/0210050]

future: KATRIN (start 2012)

[hep-ex/0109033] [hep-ex/0309007]

sensitivity: $m_{\nu_e} \simeq 0.2 \text{ eV}$

$$\text{Neutrino Mixing} \implies K(T) = \left[(Q - T) \sum_k |U_{ek}|^2 \sqrt{(Q - T)^2 - m_k^2} \right]^{1/2}$$



analysis of data is
different from the
no-mixing case:

$2N - 1$ parameters

$$\left(\sum_k |U_{ek}|^2 = 1 \right)$$

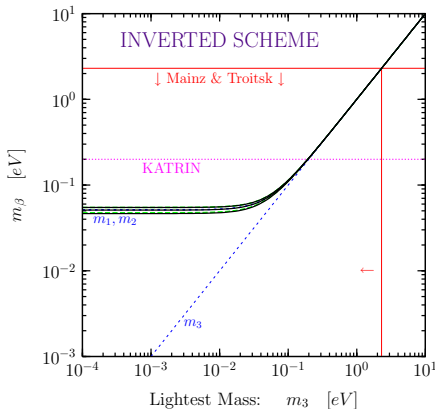
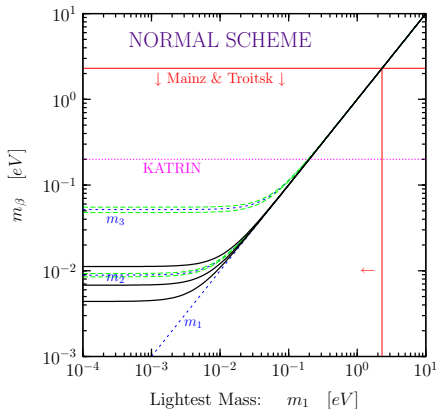
if experiment is not sensitive to masses ($m_k \ll Q - T$)

effective mass:

$$m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

$$\begin{aligned} K^2 &= (Q - T)^2 \sum_k |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q - T)^2}} \simeq (Q - T)^2 \sum_k |U_{ek}|^2 \left[1 - \frac{1}{2} \frac{m_k^2}{(Q - T)^2} \right] \\ &= (Q - T)^2 \left[1 - \frac{1}{2} \frac{m_\beta^2}{(Q - T)^2} \right] \simeq (Q - T) \sqrt{(Q - T)^2 - m_\beta^2} \end{aligned}$$

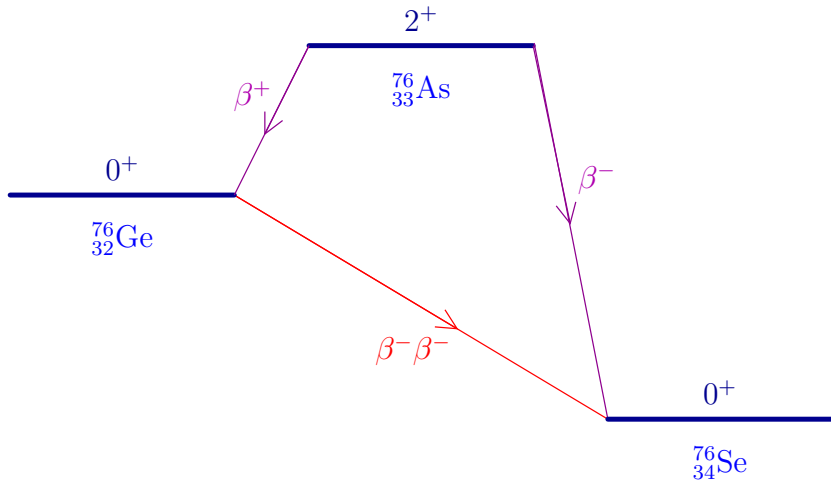
$$m_\beta^2 = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$



Quasi-Degenerate: $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \implies m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$

FUTURE: IF $m_\beta \lesssim 4 \times 10^{-2} \text{ eV} \implies$ NORMAL HIERARCHY

Neutrinoless Double-Beta Decay



Effective Majorana Neutrino Mass:

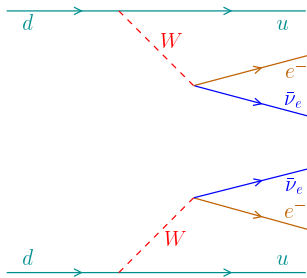
$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k$$

Two-Neutrino Double- β Decay: $\Delta L = 0$

$$\mathcal{N}(A, Z) \rightarrow \mathcal{N}(A, Z + 2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

$$(T_{1/2}^{2\nu})^{-1} = G_{2\nu} |\mathcal{M}_{2\nu}|^2$$

second order weak interaction process
in the Standard Model



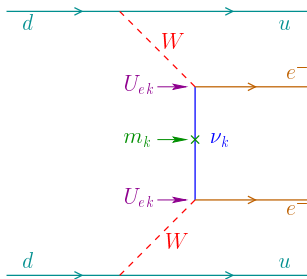
Neutrinoless Double- β Decay: $\Delta L = 2$

$$\mathcal{N}(A, Z) \rightarrow \mathcal{N}(A, Z + 2) + e^- + e^-$$

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2$$

effective
Majorana
mass

$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k$$

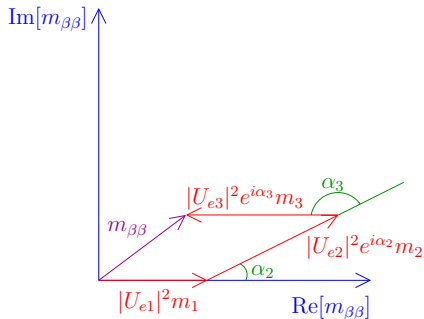
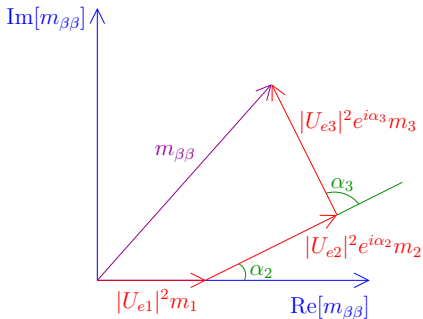


Effective Majorana Neutrino Mass

$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k \quad \text{complex } U_{ek} \Rightarrow \text{possible cancellations}$$

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$

$$\alpha_2 = 2\lambda_2 \quad \alpha_3 = 2(\lambda_3 - \delta_{13})$$



Experimental Bounds

CUORICINO (^{130}Te) [arXiv:1012.3266]

$$T_{1/2}^{0\nu} > 2.8 \times 10^{24} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.3 - 0.7 \text{ eV}$$

Heidelberg-Moscow (^{76}Ge) [EPJA 12 (2001) 147]

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.32 - 1.0 \text{ eV}$$

IGEX (^{76}Ge) [PRD 65 (2002) 092007]

$$T_{1/2}^{0\nu} > 1.57 \times 10^{25} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.33 - 1.35 \text{ eV}$$

NEMO 3 (^{100}Mo) [PRL 95 (2005) 182302]

$$T_{1/2}^{0\nu} > 4.6 \times 10^{23} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.7 - 2.8 \text{ eV}$$

FUTURE EXPERIMENTS

COBRA, XMASS, CAMEO, CANDLES

$$|m_{\beta\beta}| \sim \text{few } 10^{-1} \text{ eV}$$

EXO, MOON, Super-NEMO, CUORE, Majorana, GEM, GERDA

$$|m_{\beta\beta}| \sim \text{few } 10^{-2} \text{ eV}$$

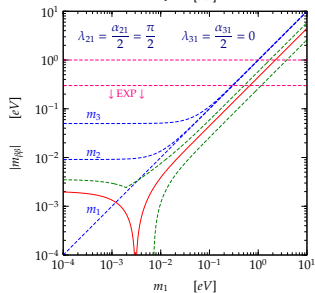
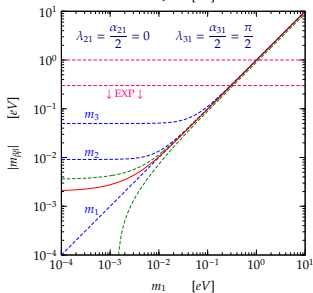
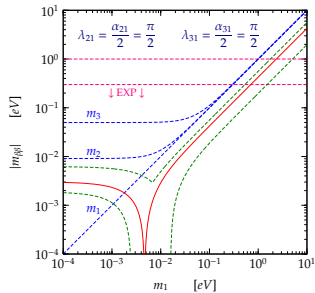
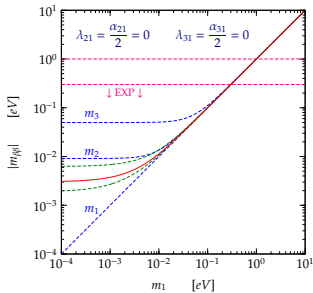
Bounds from Neutrino Oscillations

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3$$

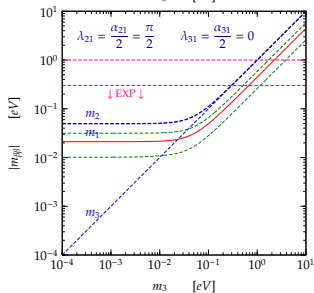
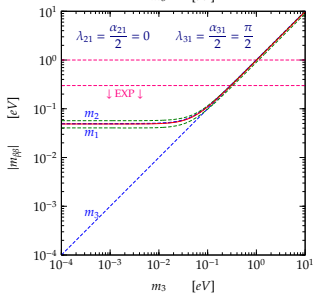
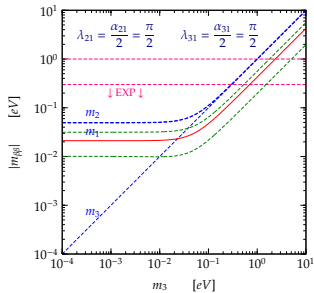
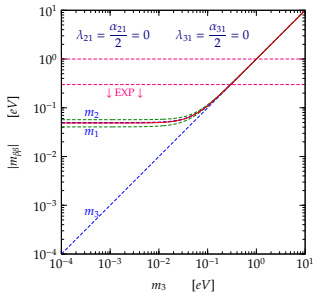
CP conservation

$$\alpha_{21} = 0, \pi \quad \alpha_{31} = 0, \pi$$

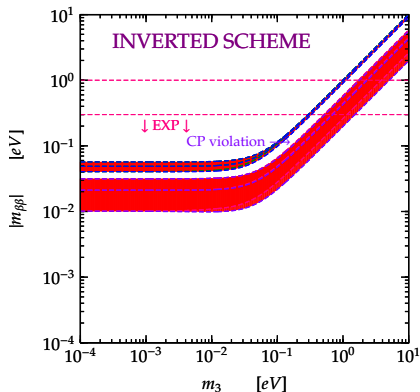
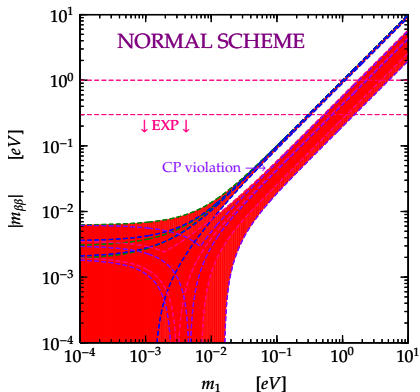
CP Conservation: Normal Scheme



CP Conservation: Inverted Scheme



$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3$$



FUTURE: IF $|m_{\beta\beta}| \lesssim 10^{-2} \text{ eV} \Rightarrow$ NORMAL HIERARCHY

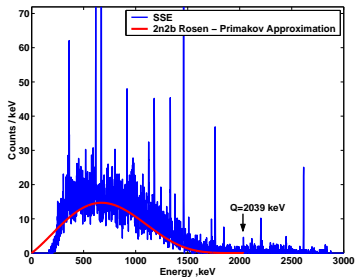
Experimental Positive Indication

[Klapdor et al., MPLA 16 (2001) 2409]

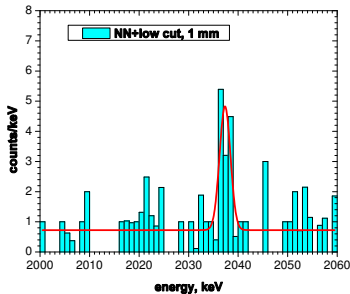
$$T_{1/2}^{0\nu} = (2.23_{-0.31}^{+0.44}) \times 10^{25} \text{ y}$$

6.5 σ evidence

[MPLA 21 (2006) 1547]



[PLB 586 (2004) 198]



[MPLA 21 (2006) 1547]

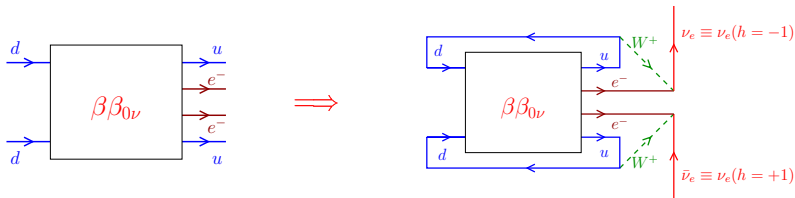
the indication must be checked by other experiments

$$|m_{\beta\beta}| = 0.32 \pm 0.03 \text{ eV}$$

[MPLA 21 (2006) 1547]

if confirmed, very exciting (Majorana ν and large mass scale)

$\beta\beta_{0\nu}$ Decay \Leftrightarrow Majorana Neutrino Mass

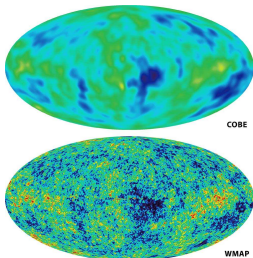


[Schechter, Valle, PRD 25 (1982) 2951] [Takasugi, PLB 149 (1984) 372]

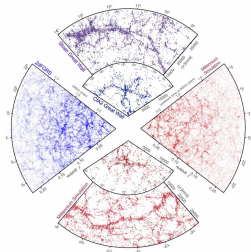
Majorana Mass Term

$$\mathcal{L}_{eL}^M = -\frac{1}{2} m_{ee} \left(\overline{\nu_{eL}^c} \nu_{eL} + \overline{\nu_{eL}} \nu_{eL}^c \right)$$

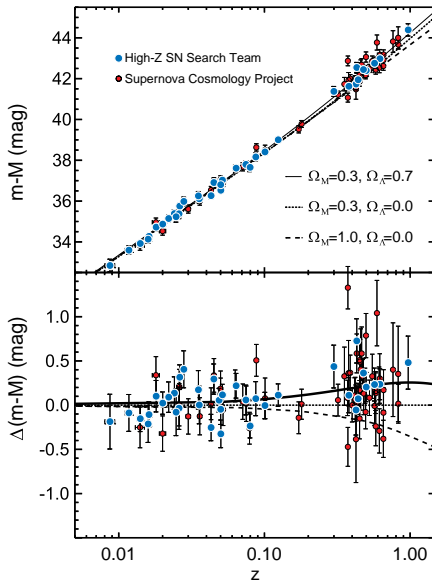
Cosmological Bound on Neutrino Masses



[WMAP, <http://map.gsfc.nasa.gov>]

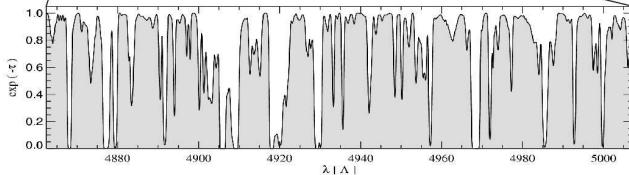
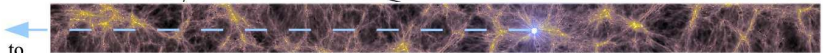
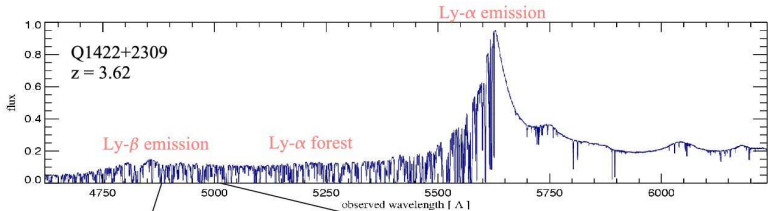


[Springel, Frenk, White, Nature 440 (2006) 1137]



[<http://cfa-www.harvard.edu/supernova/>]

Lyman-alpha Forest



[Springel, Frenk, White, astro-ph/0604561]

Rest-frame Lyman α , β , γ wavelengths: $\lambda_{\alpha}^0 = 1215.67 \text{ \AA}$, $\lambda_{\beta}^0 = 1025.72 \text{ \AA}$, $\lambda_{\gamma}^0 = 972.54 \text{ \AA}$

Lyman- α forest: The region in which only Ly α photons can be absorbed: $[(1+z_q)\lambda_{\beta}^0, (1+z_q)\lambda_{\alpha}^0]$

Relic Neutrinos

neutrinos are in equilibrium in primeval plasma through weak interaction reactions
 $\nu\bar{\nu} \rightleftharpoons e^+e^-$ $\bar{\nu}e \rightleftharpoons \bar{\nu}e$ $\bar{\nu}N \rightleftharpoons \bar{\nu}N$ $\nu_e n \rightleftharpoons pe^-$ $\bar{\nu}_e p \rightleftharpoons ne^+$ $n \rightleftharpoons pe^- \bar{\nu}_e$

weak interactions freeze out

$$\Gamma_{\text{weak}} = N\sigma v \sim G_F^2 T^5 \sim T^2/M_P \sim \sqrt{G_N T^4} \sim \sqrt{G_N \rho} \sim H \implies T_{\text{dec}} \sim 1 \text{ MeV}$$

neutrino decoupling

$$\text{Relic Neutrinos: } T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \simeq 1.945 \text{ K} \implies k T_\nu \simeq 1.676 \times 10^{-4} \text{ eV}$$

($T_\gamma = 2.725 \pm 0.001 \text{ K}$)

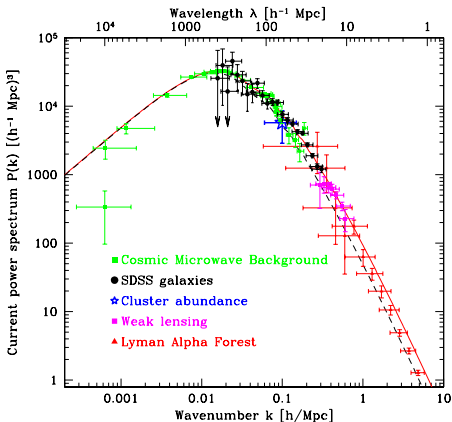
$$\text{number density: } n_f = \frac{3}{4} \frac{\zeta(3)}{\pi^2} g_f T_f^3 \implies n_{\nu_k, \bar{\nu}_k} \simeq 0.1827 T_\nu^3 \simeq 112 \text{ cm}^{-3}$$

$$\text{density contribution: } \Omega_k = \frac{n_{\nu_k, \bar{\nu}_k} m_k}{\rho_c} \simeq \frac{1}{h^2} \frac{m_k}{94.14 \text{ eV}} \implies \Omega_\nu h^2 = \frac{\sum_k m_k}{94.14 \text{ eV}}$$

($\rho_c = \frac{3H^2}{8\pi G_N}$) [Gershtein, Zeldovich, JETP Lett. 4 (1966) 120] [Cowsik, McClelland, PRL 29 (1972) 669]

$$h \sim 0.7, \quad \Omega_\nu \lesssim 0.3 \quad \implies \quad \sum_k m_k \lesssim 14 \text{ eV}$$

Power Spectrum of Density Fluctuations



[Tegmark, hep-ph/0503257]

Solid Curve: flat Λ CDM model

$$(\Omega_M^0 = 0.28, h = 0.72, \Omega_B^0/\Omega_M^0 = 0.16)$$

Dashed Curve: $\sum_{k=1}^3 m_k = 1 \text{ eV}$

hot dark matter
prevents early galaxy formation

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

$$\langle \delta(\vec{x}_1) \delta(\vec{x}_2) \rangle = \int \frac{d^3 k}{(2\pi)^3} e^{i\vec{k} \cdot \vec{x}} P(\vec{k})$$

small scale suppression

$$\frac{\Delta P(k)}{P(k)} \approx -8 \frac{\Omega_\nu}{\Omega_m}$$

$$\approx -0.8 \left(\frac{\sum_k m_k}{1 \text{ eV}} \right) \left(\frac{0.1}{\Omega_m h^2} \right)$$

for

$$k \gtrsim k_{\text{nr}} \approx 0.026 \sqrt{\frac{m_\nu}{1 \text{ eV}}} \sqrt{\Omega_m} h \text{ Mpc}^{-1}$$

[Hu, Eisenstein, Tegmark, PRL 80 (1998) 5255]

CMB (WMAP, ...) + LSS (2dFGRS) + HST + SN-Ia \implies Flat Λ CDM

$$T_0 = 13.7 \pm 0.2 \text{ Gyr} \quad h = 0.71_{-0.03}^{+0.04}$$
$$\Omega_0 = 1.02 \pm 0.02 \quad \Omega_b = 0.044 \pm 0.004 \quad \Omega_m = 0.27 \pm 0.04$$

$$\Omega_\nu h^2 < 0.0076 \quad (95\% \text{ conf.}) \implies \sum_{k=1}^3 m_k < 0.71 \text{ eV}$$

CMB + HST + SN-Ia + BAO

$$T_0 = 13.72 \pm 0.12 \text{ Gyr} \quad h = 0.705 \pm 0.013$$

$$-0.0179 < \Omega_0 - 1 < 0.0081 \quad (95\% \text{ C.L.})$$

$$\Omega_b = 0.0456 \pm 0.0015 \quad \Omega_m = 0.274 \pm 0.013$$

$$\sum_{k=1}^3 m_k < 0.67 \text{ eV} \quad (95\% \text{ C.L.}) \quad N_{\text{eff}} = 4.4 \pm 1.5$$

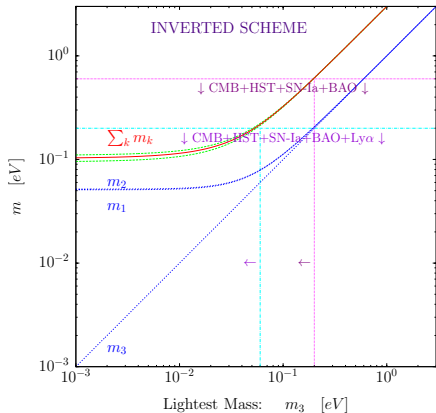
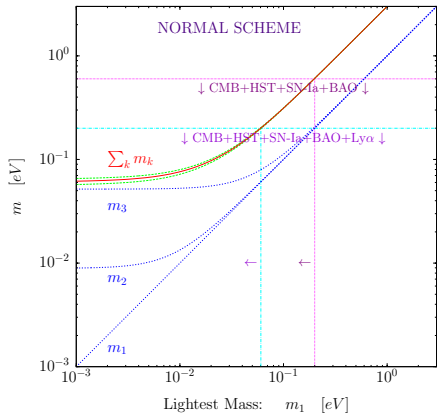
Flat Λ CDM

Case	Cosmological data set	Σ (at 2σ)
1	CMB	< 1.19 eV
2	CMB + LSS	< 0.71 eV
3	CMB + HST + SN-Ia	< 0.75 eV
4	CMB + HST + SN-Ia + BAO	< 0.60 eV
5	CMB + HST + SN-Ia + BAO + $\text{Ly}\alpha$	< 0.19 eV

2σ (95% C.L.) constraints on the sum of ν masses Σ .

$$\sum_{k=1}^3 m_k \lesssim 0.6 \text{ eV} \quad (\sim 2\sigma) \quad \text{CMB} + \text{HST} + \text{SN-Ia} + \text{BAO}$$

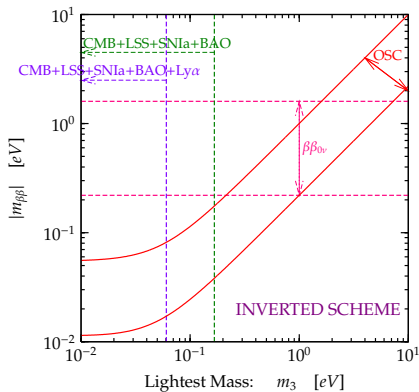
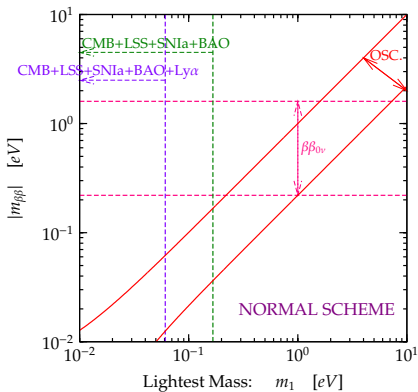
$$\sum_{k=1}^3 m_k \lesssim 0.2 \text{ eV} \quad (\sim 2\sigma) \quad \text{CMB} + \text{HST} + \text{SN-Ia} + \text{BAO} + \text{Ly}\alpha$$



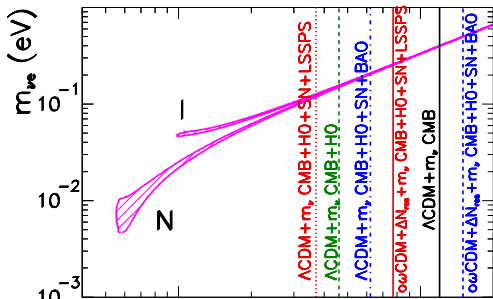
FUTURE: IF $\sum_{k=1}^3 m_k \lesssim 9 \times 10^{-2} \text{ eV} \Rightarrow$ NORMAL HIERARCHY

Indication of $\beta\beta_{0\nu}$ Decay: $0.22 \text{ eV} \lesssim |m_{\beta\beta}| \lesssim 1.6 \text{ eV}$ ($\sim 3\sigma$ range)

[Klapdor et al., MPLA 16 (2001) 2409; FP 32 (2002) 1181; NIMA 522 (2004) 371; PLB 586 (2004) 198]



tension among oscillation data, CMB+LSS+BAO(+Ly α) and $\beta\beta_{0\nu}$ signal

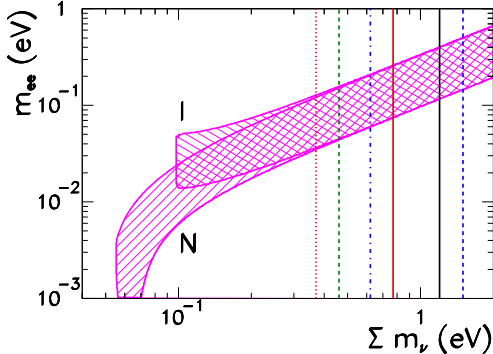


95% allowed regions (2 dof)

95% upper bounds on $\sum m_\nu$

[Gonzalez-Garcia, Maltoni, Salvado,

JHEP08 (2010) 117, arXiv:1006.3795v2]



Anomalies Beyond Three-Neutrino Mixing

- Solar Neutrinos and KamLAND
- Atmospheric and LBL Oscillation Experiments
- Phenomenology of Three-Neutrino Mixing
- Absolute Scale of Neutrino Masses
- Anomalies Beyond Three-Neutrino Mixing
- Conclusions

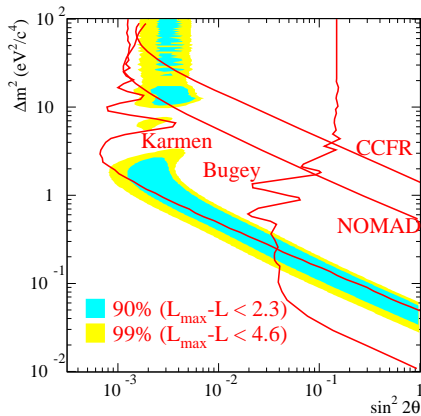
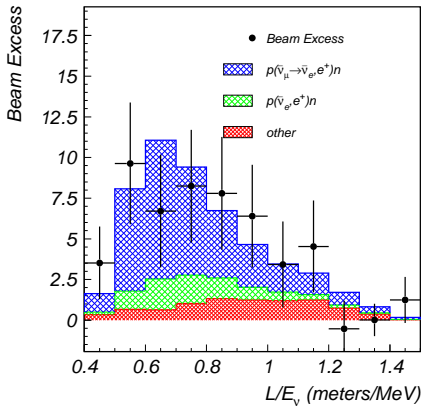
LSND

[LSND, PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

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

$$L \simeq 30 \text{ m}$$

$$20 \text{ MeV} \leq E \leq 200 \text{ MeV}$$



$$\Delta m_{\text{LSND}}^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m_{\text{ATM}}^2 \gg \Delta m_{\text{SOL}}^2)$$

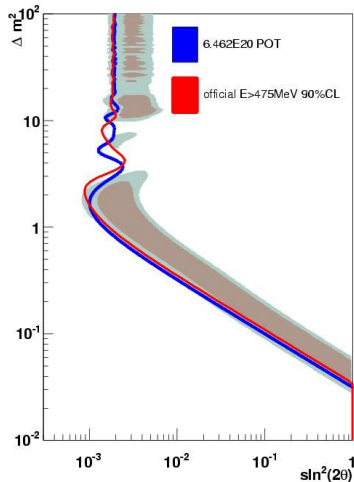
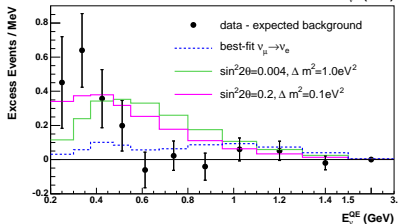
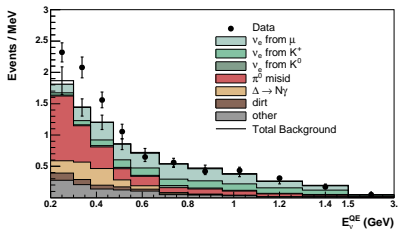
MiniBooNE Neutrinos

[PRL 98 (2007) 231801; PRL 102 (2009) 101802]

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

$$L \simeq 541 \text{ m}$$

$$475 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$$



[MiniBooNE, PRL 102 (2009) 101802, arXiv:0812.2243]

[Djurcic, arXiv:0901.1648]

Low-Energy Anomaly!

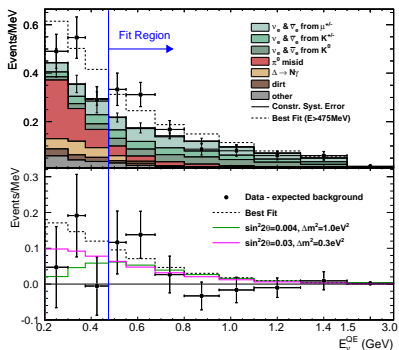
MiniBooNE Antineutrinos

[PRL 103 (2009) 111801; PRL 105 (2010) 181801]

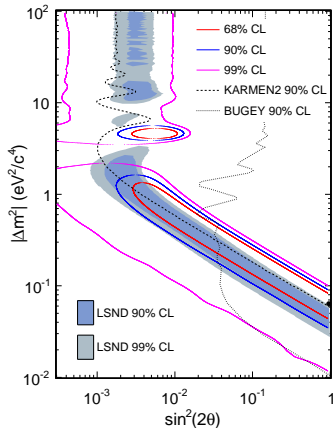
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$L \simeq 541 \text{ m}$$

$$475 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$$



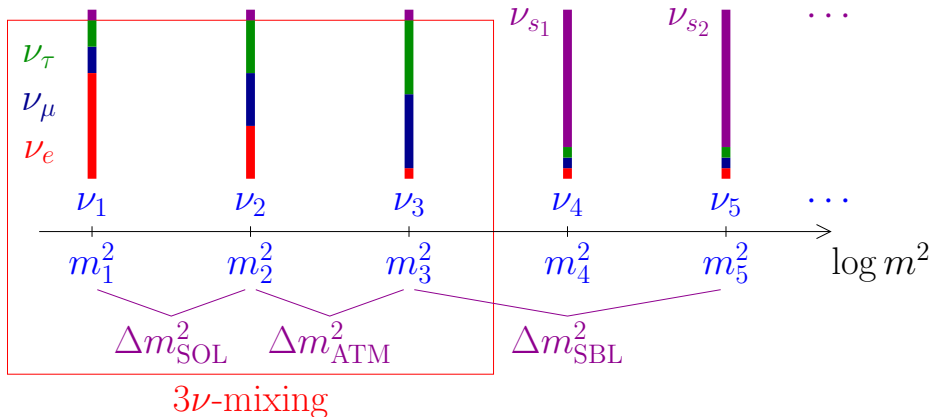
[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]



Agreement with LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal!

Similar L/E but different L and $E \Rightarrow$ Oscillations!

Beyond Three-Neutrino Mixing



Standard Model

- ▶ Neutrinos are the only massless fermions
- ▶ Neutrinos are the only fermions with only left-handed component ν_L

Extension of the SM: Massive Neutrinos

- ▶ Simplest extension: introduce right-handed component ν_R
- ▶ Dirac mass $m_D \overline{\nu_R} \nu_L$ + Majorana mass $m_M \overline{\nu_R^c} \nu_R$
- ▶ $\nu_{eL}, \nu_{\mu L}, \nu_{\tau L} + \nu_{eR}, \nu_{\mu R}, \nu_{\tau R} \implies$ 6 massive Majorana neutrinos

Sterile Neutrinos

- ▶ Light anti- ν_R are called sterile neutrinos

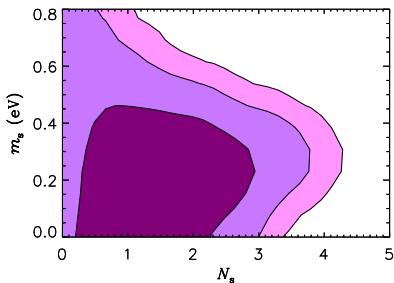
$$\nu_R^c \rightarrow \nu_s \quad (\text{left-handed})$$

- ▶ Sterile means no standard model interactions
- ▶ Active neutrinos (ν_e, ν_μ, ν_τ) can oscillate into sterile neutrinos (ν_s)
- ▶ Observables:
 - ▶ Disappearance of active neutrinos
 - ▶ Indirect evidence through combined fit of data (current indication)
- ▶ Powerful window on new physics beyond the Standard Model

Cosmology

- ▶ N_s = number of thermalized sterile neutrinos (not necessarily integer)

- ▶ CMB and LSS in Λ CDM:



[Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301, arXiv:1006.5276]

$$N_s = 1.61 \pm 0.92 \quad m_{\nu_s} < 0.70 \text{ eV} \quad (95\% \text{ C.L.})$$

[Giusarma, Corsi, Archidiacono, de Putter, Melchiorri, Mena, Pandolfi, arXiv:1102.4774]

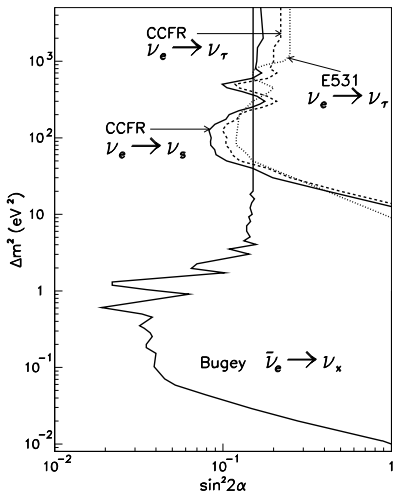
- ▶ BBN: $N_s = 0.22 \pm 0.59$ [Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313, astro-ph/0408033]

$$N_s = 0.64^{+0.40}_{-0.35} \quad [\text{Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440}]$$

Direct Searches of Active-Sterile Transitions

CCFR

[PRD 59 (1999) 031101, arXiv:hep-ex/9809023]



NC interactions

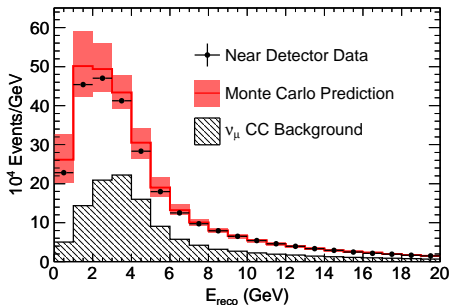
$E \sim 100 \text{ GeV}$

$L \simeq 1.4 \text{ km}$

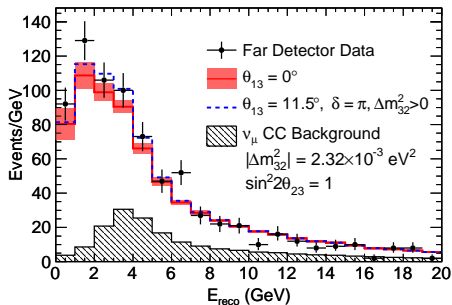
MINOS

NC sample: 89% efficiency and 61% purity
 97% of ν_e -induced CC events misidentified as NC

[arXiv:1104.3922]



$L_{ND} = 1.04 \text{ km}$



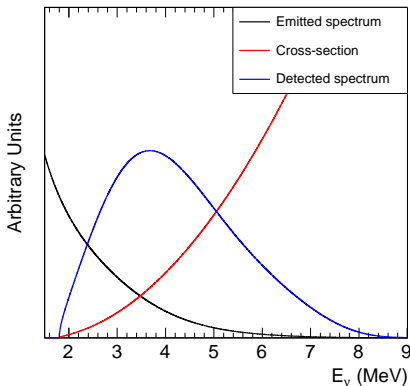
$L_{FD} = 735 \text{ km}$

Model	ϑ_{13}	$\chi^2/\text{D.O.F.}$	ϑ_{23}	ϑ_{24}	ϑ_{34}	f_s
$m_4 = m_1$	0	130.4/123	45.0^{+7}_{-7}	-	$0.0^{+17}_{-0.0}$	0.22
	11.5	128.5/123	45.6^{+7}_{-7}	-	$0.0^{+25}_{-0.0}$	0.40
$m_4 \gg m_3$	0	130.4/122	45.0^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+17}_{-0.0}$	0.22
	11.5	128.5/122	45.6^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+25}_{-0.0}$	0.40

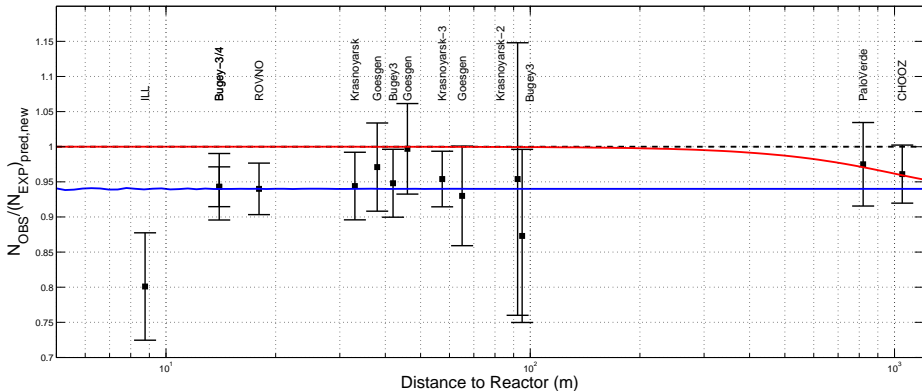
90% C.L.

New Calculation of Reactor $\bar{\nu}_e$ Flux

- ▶ Th. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, A. Porta, F. Yermia, Improved Predictions of Reactor Antineutrino Spectra, arXiv:1101.2663
- ▶ detected flux normalization is increased by about 3%

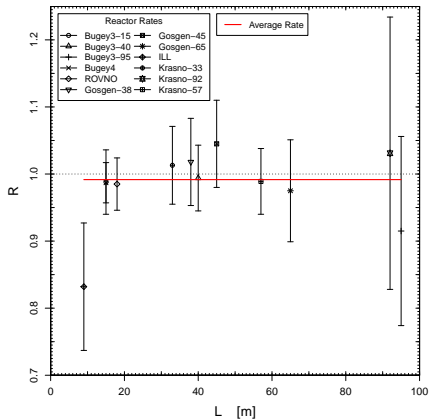


- ▶ G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D. Lhuillier, M. Cribier, A. Letourneau, **The Reactor Antineutrino Anomaly**, arXiv:1101.2755
- ▶ ratio of observed and predicted event rates: 0.937 ± 0.027
- ▶ deviation from unity at 98.4% C.L.: reactor antineutrino anomaly



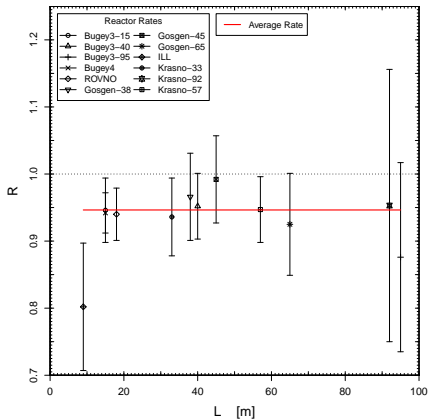
Reactor Antineutrino Anomaly

Standard Reactor $\bar{\nu}_e$ Fluxes



$$\bar{R} = 0.992 \pm 0.024$$

New Reactor $\bar{\nu}_e$ Fluxes

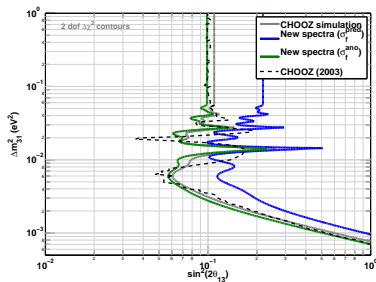


$$\bar{R} = 0.946 \pm 0.024$$

- ▶ New reactor neutrino flux has several implications: fit of solar and KamLAND data, determination of ϑ_{13} , short-baseline $\bar{\nu}_e$ disappearance, ...

Chooz limit on ϑ_{13}

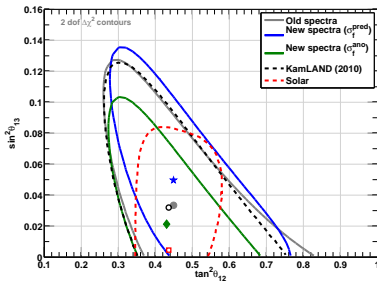
[Chooz, EPJC 27 (2003) 331]



[Mention et al., arXiv:1101.2755]

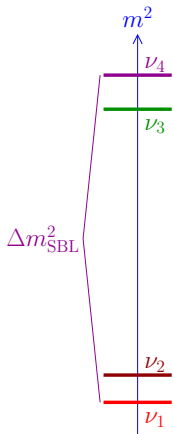
Hint of $\vartheta_{13} > 0$

[Fogli et al., PRL 101 (2008) 141801]

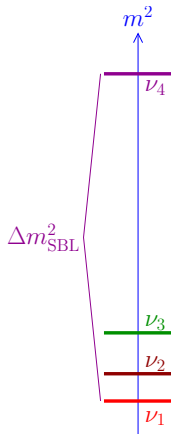


[Mention et al., arXiv:1101.2755]

Four-Neutrino Schemes: 2+2 and 3+1

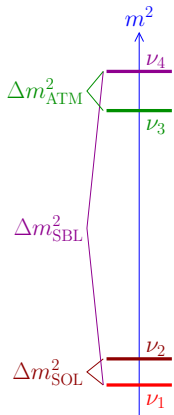


"2+2"

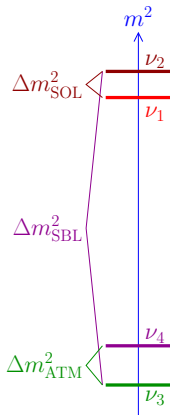


"3+1"

2+2 Four-Neutrino Schemes

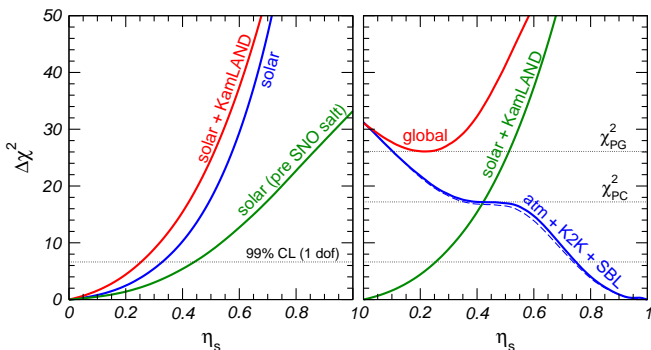


"normal"



"inverted"

2+2 Schemes are strongly disfavored by solar and atmospheric data



matter effects + SNO NC

matter effects

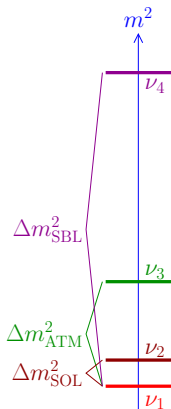
$$\eta_s = |U_{s1}|^2 + |U_{s2}|^2$$

$$1 - \eta_s = |U_{s3}|^2 + |U_{s4}|^2$$

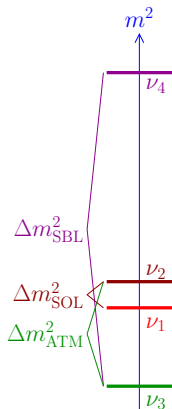
99% CL: $\begin{cases} \eta_s < 0.25 & \text{(solar + KamLAND)} \\ \eta_s > 0.75 & \text{(atmospheric + K2K)} \end{cases}$

[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

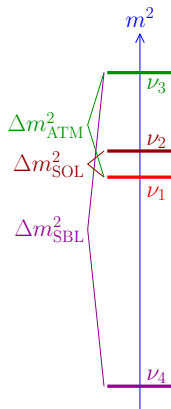
3+1 Four-Neutrino Schemes



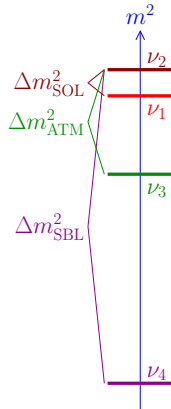
"normal"



"3 ν -inverted"



"4 ν -inverted"



"fully-inverted"

Perturbation of 3- ν Mixing

$$|U_{e4}|^2 \ll 1$$

$$|U_{\mu 4}|^2 \ll 1$$

$$|U_{\tau 4}|^2 \ll 1$$

$$|U_{s4}|^2 \simeq 1$$

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$\begin{aligned}
 P_{\nu_\alpha \rightarrow \nu_\beta} &= \left| \sum_{k=1}^4 U_{\alpha k}^* U_{\beta k} e^{-iE_k t} \right|^2 * \left| e^{iE_1 t} \right|^2 \\
 &= \left| \sum_{k=1}^4 U_{\alpha k}^* U_{\beta k} e^{-i(E_k - E_1)t} \right|^2 \rightarrow \left| \sum_{k=1}^4 U_{\alpha k}^* U_{\beta k} \exp\left(\frac{\Delta m_{k1}^2 L}{2E}\right) \right|^2
 \end{aligned}$$

$$E_k \simeq E + \frac{m_k^2}{2E} \quad \frac{\Delta m_{21}^2 L}{2E} \ll 1 \quad \frac{\Delta m_{31}^2 L}{2E} \ll 1 \quad \Delta m_{41}^2 \rightarrow \Delta m^2$$

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \left| U_{\alpha 1}^* U_{\beta 1} + U_{\alpha 2}^* U_{\beta 2} + U_{\alpha 3}^* U_{\beta 3} + U_{\alpha 4}^* U_{\beta 4} \exp\left(\frac{\Delta m^2 L}{2E}\right) \right|^2$$

$$U_{\alpha 1}^* U_{\beta 1} + U_{\alpha 2}^* U_{\beta 2} + U_{\alpha 3}^* U_{\beta 3} = \delta_{\alpha\beta} - U_{\alpha 4}^* U_{\beta 4}$$

$$\begin{aligned}
P_{\nu_\alpha \rightarrow \nu_\beta} &= \left| \delta_{\alpha\beta} - U_{\alpha 4}^* U_{\beta 4} \left[1 - \exp\left(\frac{\Delta m^2 L}{2E}\right) \right] \right|^2 \\
&= \delta_{\alpha\beta} + |U_{\alpha 4}|^2 |U_{\beta 4}|^2 \left(2 - 2 \cos \frac{\Delta m^2 L}{2E} \right) \\
&\quad - 2\delta_{\alpha\beta} |U_{\alpha 4}|^2 \left(1 - \cos \frac{\Delta m^2 L}{2E} \right) \\
&= \delta_{\alpha\beta} - 2|U_{\alpha 4}|^2 \left(\delta_{\alpha\beta} - |U_{\beta 4}|^2 \right) \left(1 - \cos \frac{\Delta m^2 L}{2E} \right) \\
&= \delta_{\alpha\beta} - 4|U_{\alpha 4}|^2 \left(\delta_{\alpha\beta} - |U_{\beta 4}|^2 \right) \sin^2 \frac{\Delta m^2 L}{2E}
\end{aligned}$$

$$\alpha \neq \beta \implies P_{\nu_\alpha \rightarrow \nu_\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$\alpha = \beta \implies P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2 \right) \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

No CP Violation!

$$P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

Perturbation of 3ν Mixing

$$|U_{e4}|^2 \ll 1, \quad |U_{\mu 4}|^2 \ll 1, \quad |U_{\tau 4}|^2 \ll 1, \quad |U_{s4}|^2 \simeq 1$$

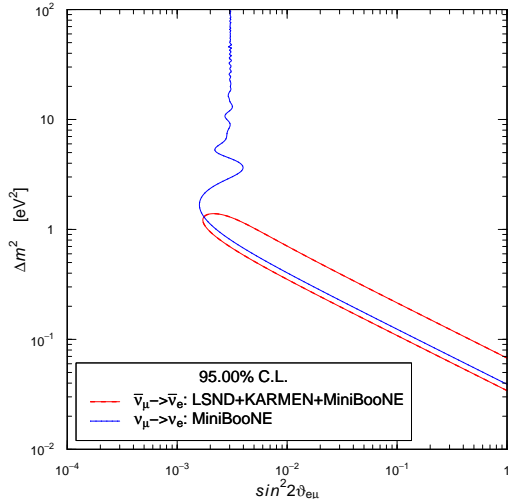
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

↑
SBL

$$\sin^2 2\vartheta_{\alpha\alpha} \ll 1$$



$$|U_{\alpha 4}|^2 \simeq \frac{\sin^2 2\vartheta_{\alpha\alpha}}{4}$$



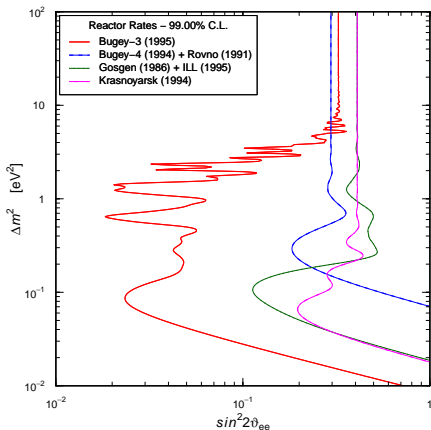
3+1 Schemes

GoF = 32%

PGoF = 0.89%

- ▶ Tension between LSND + KARMEN + MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and MiniBooNE $\nu_\mu \rightarrow \nu_e \implies$ CP Violation?
- ▶ 3+2 \implies CP Violation OK [Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004, hep-ph/0305255; Maltoni, Schwetz, PRD 76, 093005 (2007), arXiv:0705.0107; Karagiorgi et al, PRD 80 (2009) 073001, arXiv:0906.1997]
- ▶ 3+1+NSI \implies CP Violation OK [Akhmedov, Schwetz, JHEP 10 (2010) 115, arXiv:1007.4171]

$\bar{\nu}_e$ Disappearance

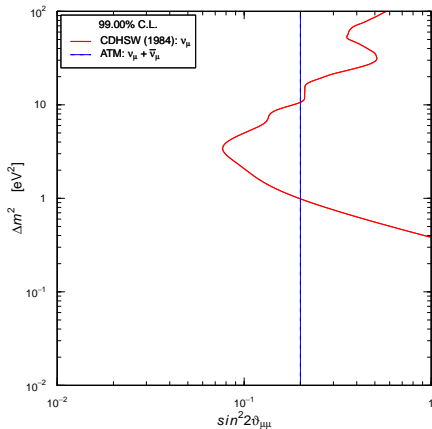


New Reactor $\bar{\nu}_e$ Fluxes

[Mueller et al., arXiv:1101.2663]

[Mention et al., arXiv:1101.2755]

ν_μ and $\bar{\nu}_\mu$ Disappearance



ATM constraint on $|U_{\mu 4}|^2$

[Maltoni, Schwetz, PRD 76 (2007) 093005, arXiv:0705.0107]

- ▶ ν_e disappearance experiments:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 (1 - |U_{e4}|^2) \simeq 4|U_{e4}|^2$$

- ▶ ν_μ disappearance experiments:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 (1 - |U_{\mu4}|^2) \simeq 4|U_{\mu4}|^2$$

- ▶ $\nu_\mu \rightarrow \nu_e$ experiments:

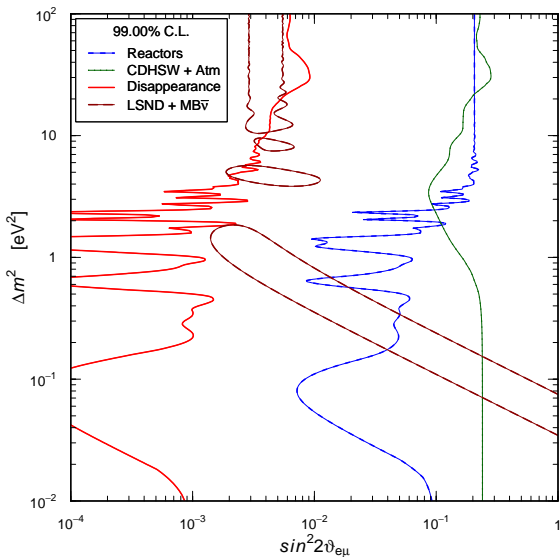
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

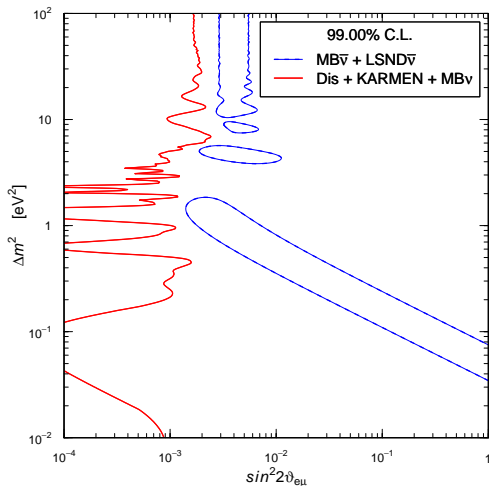
- ▶ Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \implies$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694, arXiv:hep-ph/9606411]

[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247, arXiv:hep-ph/9607372]

3+1 Schemes





PGoF = 0.006%

- ▶ Strong tension between $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance and disappearance limits ($\bar{\nu}_e \rightarrow \bar{\nu}_e$ and mainly $\nu_\mu \rightarrow \nu_\mu$)
- ▶ Tension reduced in 3+2, 3+1+NSI
- ▶ CPT Violation? [Barger, Marfatia, Whisnant, PLB 576 (2003) 303]
[Giunti, Laveder, PRD 82 (2010) 093016, PRD 83 (2011) 053006]

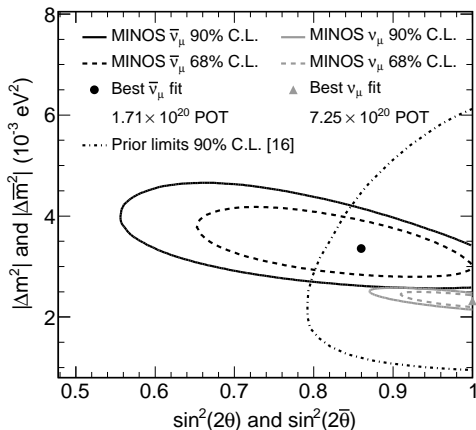
MINOS Hint of CPT Violation?

LBL ν_μ and $\bar{\nu}_\mu$ disappearance

$E \sim 3 \text{ GeV}$

Near Detector at 1.04 km

Far Detector at 735 km



$$|\Delta m^2| = \left(2.32^{+0.12}_{-0.08} \right) \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\vartheta > 0.90 \quad (90\% \text{ C.L.})$$

[arXiv:1103.0340v1]

$$|\Delta \bar{m}^2| = \left(3.36^{+0.46}_{-0.40} \right) \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\bar{\vartheta} = 0.86^{+0.11}_{-0.12}$$

[arXiv:1104.0344v2]

CDF Hint of CPT Violation?

Measurement of the mass difference between t and \bar{t} quarks,

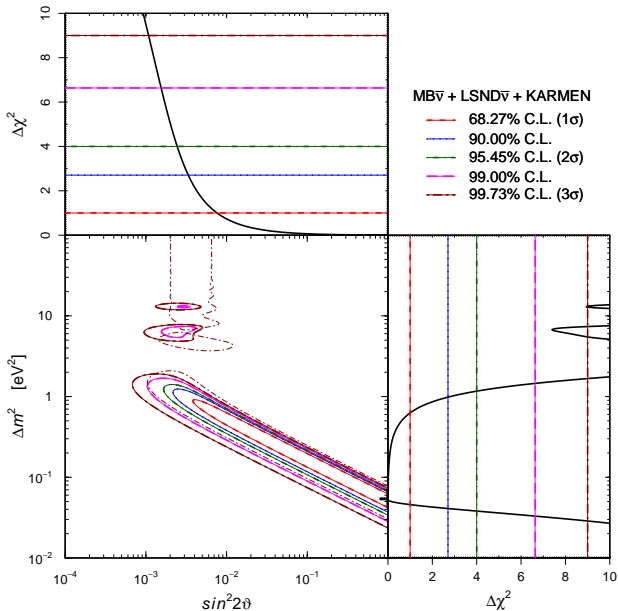
arXiv:1103.2782v1 [hep-ex]

$$m_t - m_{\bar{t}} = -3.3 \pm 1.4 \pm 1.0 \text{ GeV}$$

“approximately two standard deviations away from the CPT hypothesis of zero mass difference”

Phenomenological Approach: Consider $\bar{\nu}$'s Only

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



$$\chi^2_{\min} = 29.8$$

$$\text{NdF} = 26$$

$$\text{GoF} = 28\%$$

$$\sin^2 2\vartheta = 1.00$$

$$\Delta m^2 = 0.052 \text{ eV}^2$$

Parameter
Goodness-of-Fit

$$\Delta\chi^2_{\min} = 5.9$$

$$\text{NdF} = 4$$

$$\text{GoF} = 21\%$$

[Giunti, Laveder, PRD 82 (2010)

093016, arXiv:1010.1395]

Conservation of Probability

$$\sum_{\alpha} P_{\bar{\nu}_{\alpha} \rightarrow \bar{\nu}_e} = 1$$

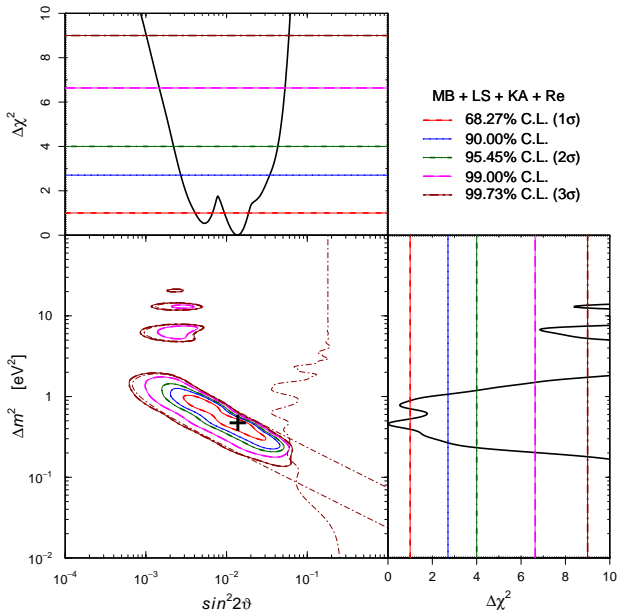
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} + P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e} + P_{\bar{\nu}_{\tau} \rightarrow \bar{\nu}_e} + P_{\bar{\nu}_s \rightarrow \bar{\nu}_e} = 1$$

$$P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e} = 1 - P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} - P_{\bar{\nu}_{\tau} \rightarrow \bar{\nu}_e} - P_{\bar{\nu}_s \rightarrow \bar{\nu}_e}$$

$$P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e} \leq 1 - P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$$

Reactor $\bar{\nu}_e$ disappearance bound is unavoidable!

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\bar{\nu}_e \rightarrow \bar{\nu}_e$



$$\chi_{\min}^2 = 81.4$$

$$\text{NdF} = 82$$

$$\text{GoF} = 50\%$$

$$\sin^2 2\vartheta = 0.014$$

$$\Delta m^2 = 0.46 \text{ eV}^2$$

Parameter
Goodness-of-Fit

$$\Delta\chi_{\min}^2 = 3.0$$

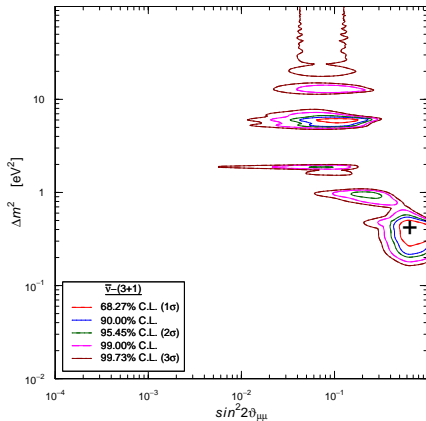
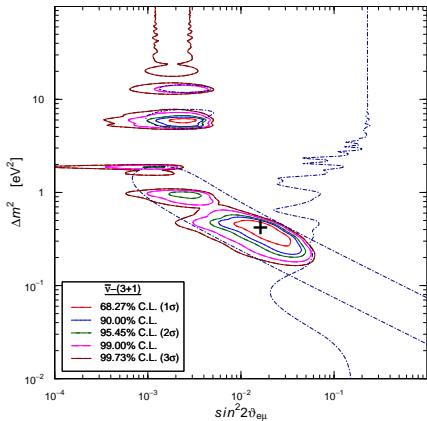
$$\text{NdF} = 2$$

$$\text{GoF} = 22\%$$

[Giunti, Laveder, PRD 82 (2010)

093016, arXiv:1010.1395]

Antineutrino Oscillations in 3+1 Schemes



$$\chi^2_{\min} = 87.0 \quad \text{NdF} = 83 \quad \text{GoF} = 36\%$$

$$\Delta m^2 = 0.42 \text{ eV}^2 \quad \sin^2 2\vartheta_{e\mu} = 0.016 \quad \sin^2 2\vartheta_{ee} = 0.020 \quad \sin^2 2\vartheta_{\mu\mu} = 0.65$$

Prediction: large SBL $\bar{\nu}_\mu$ disappearance at $\Delta m^2 \gtrsim 0.1 \text{ eV}^2$

[Giunti, Laveder, PRD 83 (2011) 053006, arXiv:1012.0267]

Gallium Anomaly

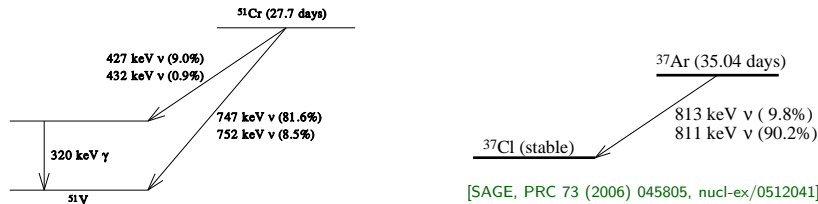
Gallium Radioactive Source Experiments

Tests of the solar neutrino detectors **GALLEX** (Cr1, Cr2) and **SAGE** (Cr, Ar)

Detection Process: $\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$

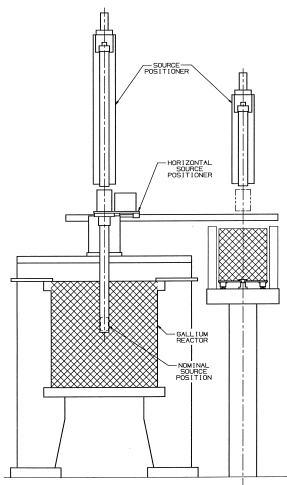
ν_e Sources: $e^- + {}^{51}\text{Cr} \rightarrow {}^{51}\text{V} + \nu_e$ $e^- + {}^{37}\text{Ar} \rightarrow {}^{37}\text{Cl} + \nu_e$

	${}^{51}\text{Cr}$				${}^{37}\text{Ar}$	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

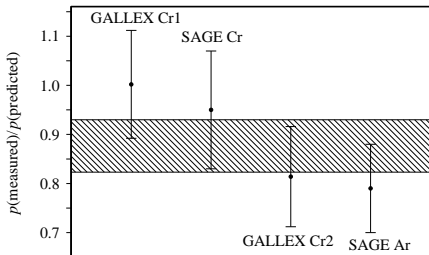
[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]

$$\langle L \rangle_{\text{GALLEX}} = 1.9 \text{ m}$$

$$\langle L \rangle_{\text{SAGE}} = 0.6 \text{ m}$$



[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

$$R_B^{\text{Gallex-Cr1}} = 0.953 \pm 0.11$$

$$R_B^{\text{Gallex-Cr2}} = 0.812^{+0.10}_{-0.11}$$

$$R_B^{\text{SAGE-Cr}} = 0.95 \pm 0.12$$

$$R_B^{\text{SAGE-Ar}} = 0.791^{+0.084}_{-0.078}$$

$$R_B^{\text{Ga}} = 0.86 \pm 0.05$$

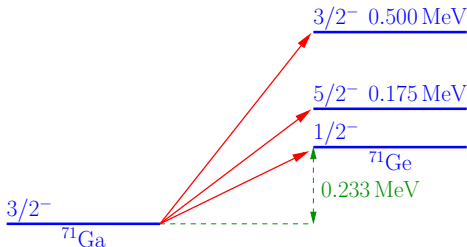
Bahcall cross section

Only exp uncertainties!

- ▶ Deficit could be due to overestimate of

$$\sigma(\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-)$$

- ▶ Calculation: Bahcall, PRC 56 (1997) 3391, hep-ph/9710491



- ▶ $\sigma_{\text{G.S.}}$ related to measured $\sigma(e^- + {}^{71}\text{Ge} \rightarrow {}^{71}\text{Ga} + \nu_e)$:

$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = 55.3 \times 10^{-46} \text{ cm}^2 (1 \pm 0.004)_{3\sigma}$$

- ▶ $\sigma({}^{51}\text{Cr}) = \sigma_{\text{G.S.}}({}^{51}\text{Cr}) \left(1 + 0.669 \frac{\text{BGT}_{175 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} + 0.220 \frac{\text{BGT}_{500 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} \right)$

- ▶ Contribution of Excited States only 5%!

► Bahcall:

[Bahcall, PRC 56 (1997) 3391, hep-ph/9710491]

from $p + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + n$ measurements [Krofcheck et al., PRL 55 (1985) 1051]

$$\frac{\text{BGT}_{175 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \Rightarrow \frac{\text{BGT}_{175 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} = \frac{0.056}{2} \quad \frac{\text{BGT}_{500 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146$$

$$3\sigma \text{ lower limit: } \frac{\text{BGT}_{175 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} = \frac{\text{BGT}_{500 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} = 0$$

$$3\sigma \text{ upper limit: } \frac{\text{BGT}_{175 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \times 2 \quad \frac{\text{BGT}_{500 \text{ keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146 \times 2$$

$$\sigma({}^{51}\text{Cr}) = 58.1 \times 10^{-46} \text{ cm}^2 \left(1_{-0.028}^{+0.036} \right)_{1\sigma} \Rightarrow R_{\text{B}}^{\text{Ga}} = 0.86 \pm 0.06$$

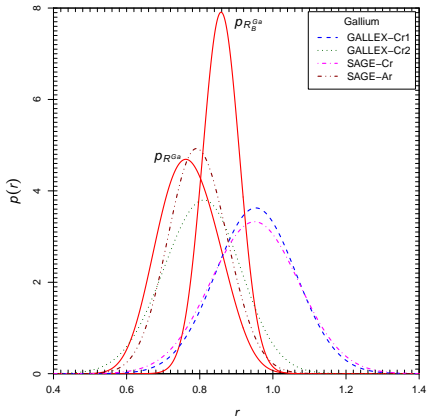
► Haxton:

[Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

“a sophisticated shell model calculation is performed ... for the transition to the first excited state in ${}^{71}\text{Ge}$. The calculation predicts destructive interference between the (p, n) spin and spin-tensor matrix elements.”

$$\sigma({}^{51}\text{Cr}) = 63.9 \times 10^{-46} \text{ cm}^2 (1 \pm 0.106)_{1\sigma} \Rightarrow R_{\text{H}}^{\text{Ga}} = 0.78 \pm 0.13$$

- ▶ $R_H^{\text{Ga}} = 0.78 \pm 0.13$ exp and the uncertainties added in quadrature
- ▶ $R^{\text{Ga}} = R_{\text{exp}}^{\text{Ga}} / R_{\text{the}}^{\text{Ga}}$ probability distribution of ratio is not Gaussian



$$p_{R^{\text{Ga}}}(r) = \int_{R_{\text{gs}}^{\text{Ga}}}^{\infty} p_{R_{\text{exp}}^{\text{Ga}}}(rs) p_{R_{\text{the}}^{\text{Ga}}}(s) s ds$$

$$R^{\text{Ga}} = 0.76^{+0.09}_{-0.08}$$

$$\begin{aligned}
 R^{\text{Gallex-Cr1}} &= 0.84^{+0.13}_{-0.12} \\
 R^{\text{Gallex-Cr2}} &= 0.71^{+0.12}_{-0.11} \\
 R^{\text{SAGE-Cr}} &= 0.84^{+0.14}_{-0.13} \\
 R^{\text{SAGE-Ar}} &= 0.70^{+0.10}_{-0.09}
 \end{aligned}$$

[Giunti, Laveder, arXiv:1006.3244]

Gallium Radioactive Source Experiments
are
Short-BaseLine Neutrino Oscillation Experiments

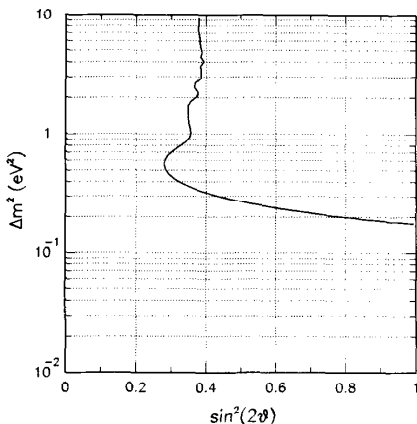


Fig. 1. Region of electron neutrino oscillation parameters ruled out at 90% C.L. by the GALLEX ^{51}Cr source experiment.

[Bahcall, Krastev, Lisi, PLB 348 (1995) 121]

$$P_{\nu_e \rightarrow \nu_e}^{\text{SBL}}(L, E) = 1 - \sin^2 2\vartheta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$R^k(\sin^2 2\vartheta, \Delta m^2) = \frac{\int_k dV L^{-2} \sum_i b_i^k \sigma_i^k P_{\nu_e \rightarrow \nu_e}^{\text{SBL}}(L, E_i)}{\sum_i b_i^k \sigma_i^k \int_k dV L^{-2}}$$

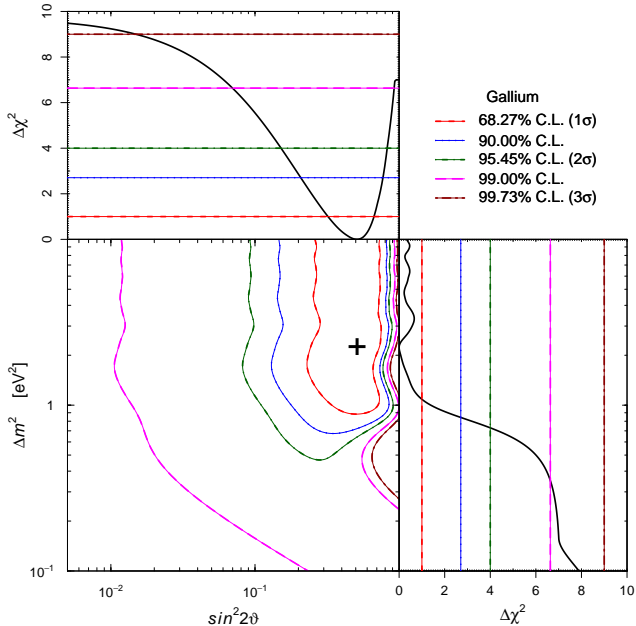
$k = \text{GALLEX-Cr1, GALLEX-Cr2, SAGE-Cr, SAGE-Ar}$

$R^k = R_{\text{exp}}^k / R_{\text{the}}^k$ fully correlated theoretical uncertainty!

$$p_{\vec{R}}(\vec{r}) = \int_{R_{\text{gs}}^k}^{\infty} \left[\prod_k p_{R_{\text{exp}}^k}(r^k s) \right] p_{R_{\text{the}}^k}(s) s^4 ds$$

$$\mathcal{L}(\sin^2 2\vartheta, \Delta m^2) = p_{\vec{R}}(\vec{R}(\sin^2 2\vartheta, \Delta m^2))$$

$$\chi^2(\sin^2 2\vartheta, \Delta m^2) = -2 \ln \mathcal{L}(\sin^2 2\vartheta, \Delta m^2) + \text{constant}$$



[Giunti, Laveder, arXiv:1006.3244]

$$\Delta\chi_{\text{No Osc.}}^2 = 9.7$$

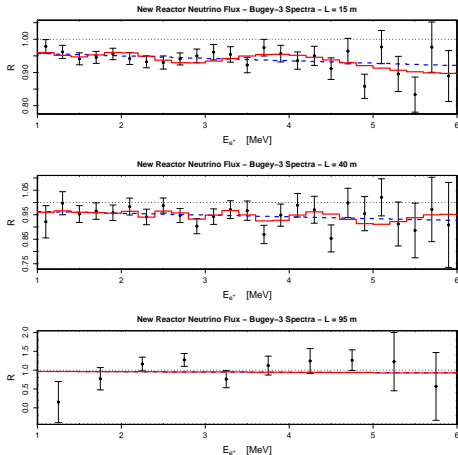
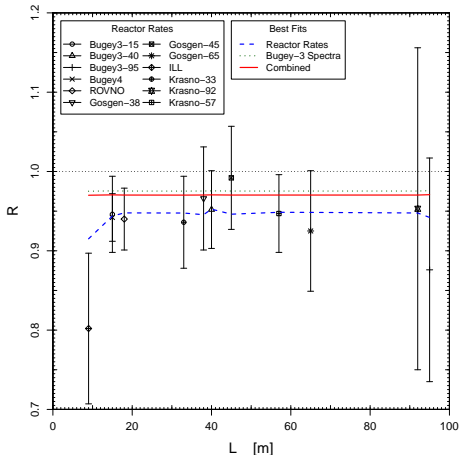
No Osc. disfavored
at 99.23 % C.L
(2.7σ)

Osc.

$$\sin^2 2\theta_{\text{bf}} = 0.51$$

$$\Delta m_{\text{bf}}^2 = 2.24 \text{ eV}^2$$

Reactor Antineutrino Anomaly



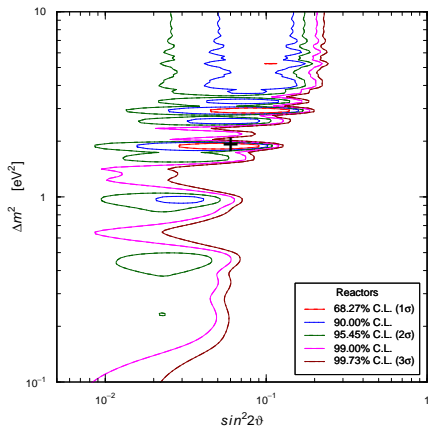
▶ $\bar{R}_{\text{rates}} = 0.946 \pm 0.024$

▶ Improved hint of oscillations given by Bugey energy spectrum with old reactor fluxes

[Acero, Giunti, Laveder, PRD 78 (2008) 073009, arXiv:0711.4222]

▶ $\sin^2 2\vartheta_{\text{bf}} = 0.059$ $\Delta m_{\text{bf}}^2 = 1.89 \text{ eV}^2$

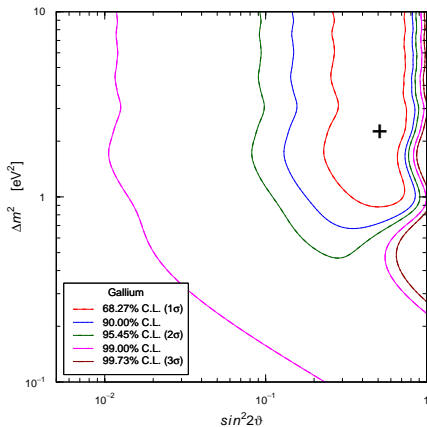
Reactor Antineutrino Anomaly



$$\sin^2 2\vartheta_{\text{bf}} = 0.059$$

$$\Delta m_{\text{bf}}^2 = 1.89 \text{ eV}^2$$

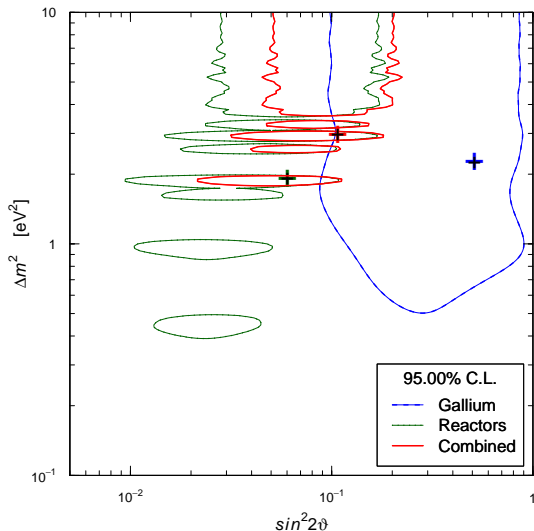
Gallium Neutrino Anomaly



$$\sin^2 2\vartheta_{\text{bf}} = 0.51$$

$$\Delta m_{\text{bf}}^2 = 2.24 \text{ eV}^2$$

Gallium Anomaly + Reactor Anomaly



$$\chi_{\min}^2 = 59.6$$

$$\text{NdF} = 71$$

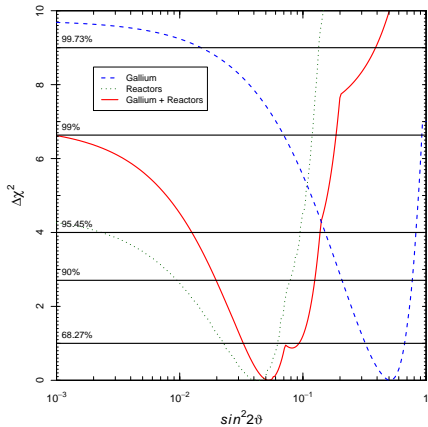
$$\text{GoF} = 83\%$$

$$\sin^2 2\theta = 0.11$$

$$\Delta m^2 = 2.95 \text{ eV}^2$$

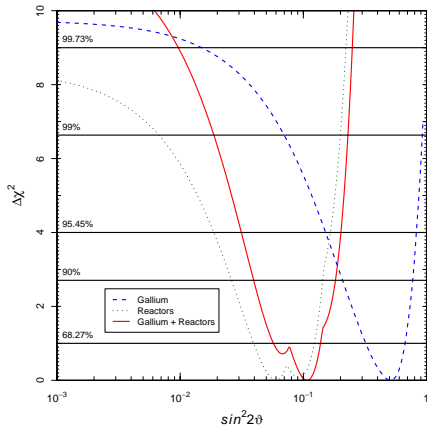
$$\text{PGoF} = 4.6\%$$

Old Reactor $\bar{\nu}_e$ Fluxes



PGoF = 2.3%

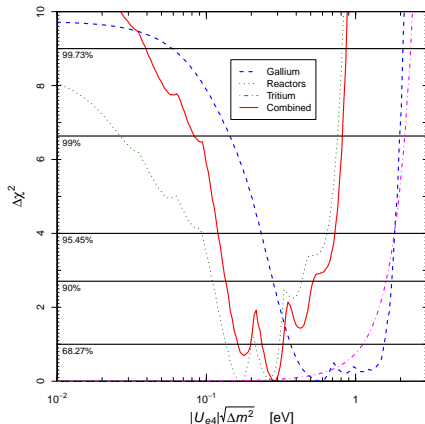
New Reactor $\bar{\nu}_e$ Fluxes



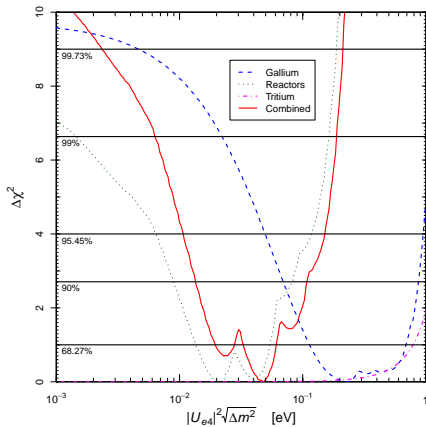
PGoF = 4.6%

Implications of Gallium and Reactor Anomalies

β Decay



$(\beta\beta)_{0\nu}$ Decay

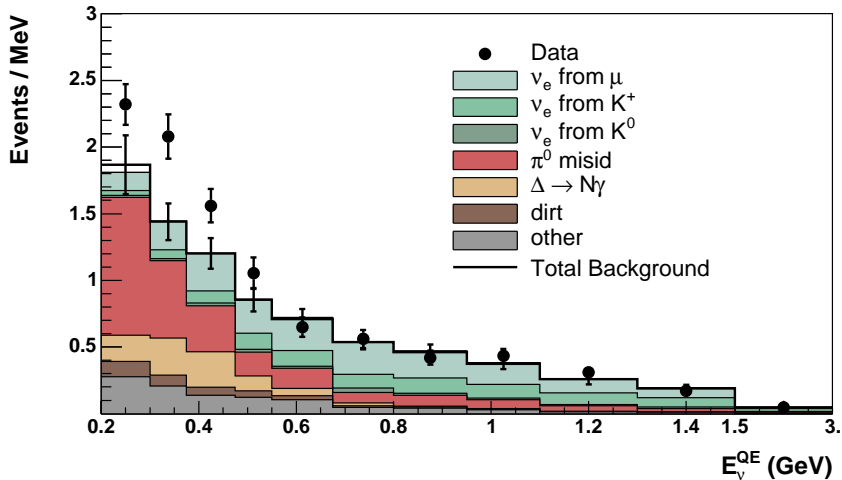


$$m_{\beta}^2 = \sum_k |U_{ek}|^2 m_k^2$$

$$m_{\beta\beta} = \left| \sum_k U_{ek}^2 m_k \right|$$

[Giunti, Laveder, In Preparation]

MiniBooNE Low-Energy Anomaly



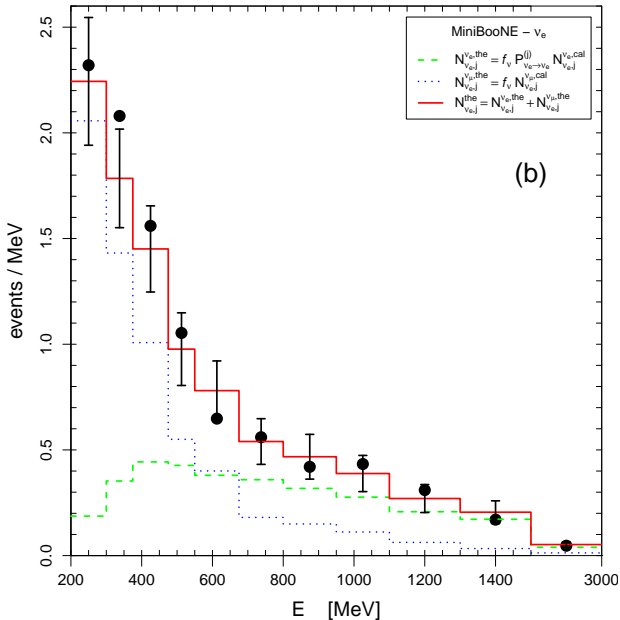
[PRL 102 (2009) 101802, arXiv:0812.2243]

Our Hypothesis:
$$N_{\nu_j}^{\text{the}} = f_\nu \left(P_{\nu_e \rightarrow \nu_e} N_{\nu_{e,j}}^{\text{cal}} + N_{\nu_{\mu,j}}^{\text{cal}} \right)$$

[Giunti, Laveder, PRD 77 (2008) 093002, arXiv:0707.4593; PRD 80 (2009) 013005, arXiv:0902.1992]

$$N_{\nu,j}^{\text{the}} = f_{\nu} \left(P_{\nu_e \rightarrow \nu_e} N_{\nu_e,j}^{\text{cal}} + N_{\nu_{\mu},j}^{\text{cal}} \right)$$

- ▶ Estimated 15% uncertainty of the calculated neutrino flux [MiniBooNE, PRD 79 (2009) 072002, arXiv:0806.1449] is consistent with measured ratio 1.21 ± 0.24 of detected and predicted charged-current quasi-elastic ν_{μ} events [MiniBooNE, PRL 100 (2008) 032301, arXiv:0706.0926]
- ▶ We fit MiniBooNE ν_e and ν_{μ} data using the info at http://www-boone.fnal.gov/for_physicists/data_release/lowe/



No Osc. & $f_\nu = 1$

$\chi^2_{\min} = 14.3 + 5.4$

NdF = 3 + 16

GoF = 41%

Our Hypothesis

$\chi^2_{\min} = 2.0 + 7.6$

NdF = 16

GoF = 89%

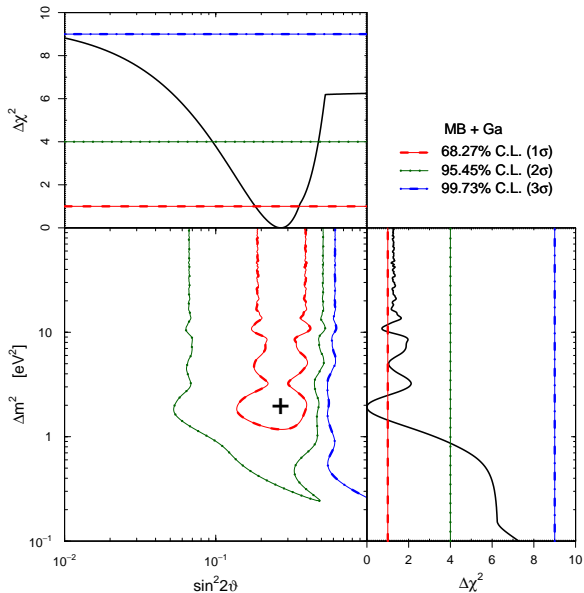
$f_\nu = 1.26$

$\sin^2 2\vartheta = 0.32$

$\Delta m^2 = 1.84 \text{ eV}^2$

[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

MiniBooNE + Gallium



$$\chi_{\min}^2 = 2.3 + 9.2$$

$$\text{NdF} = 20$$

$$\text{GoF} = 93\%$$

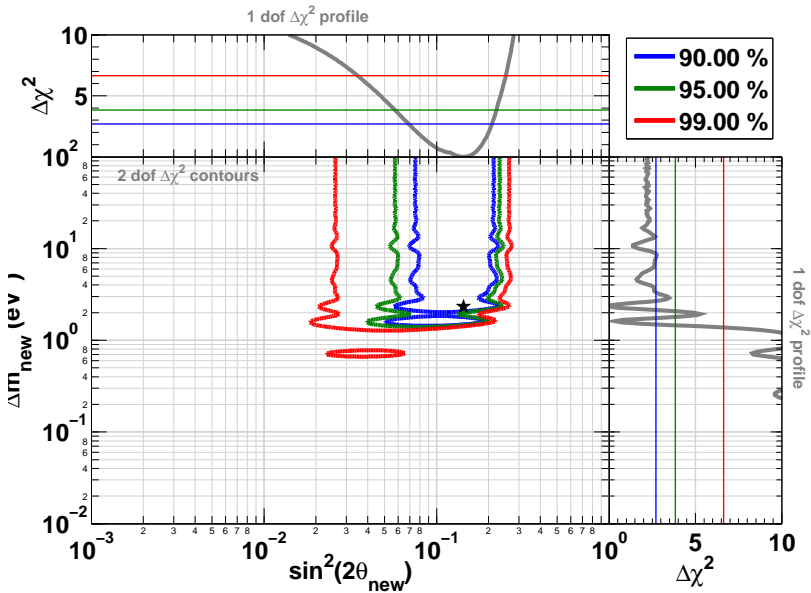
$$\sin^2 2\vartheta = 0.27$$

$$\Delta m^2 = 1.92 \text{ eV}^2$$

$$\text{PGoF} = 93\%$$

[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

MiniBooNE + Gallium + Reactors



[Mention et al., arXiv:1101.2755]

Future

- ▶ MiniBooNE is continuing to take antineutrino data.

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e + \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

- ▶ ICARUS@CERN-PS: $L \sim 1\text{km}$ $E \sim 1\text{GeV}$ [C. Rubbia et al, CERN-SPSC-2011-012]

$$\bar{\nu}_\mu^{(-)} \rightarrow \bar{\nu}_e^{(-)} + \bar{\nu}_\mu^{(-)} \rightarrow \bar{\nu}_\mu^{(-)} + \bar{\nu}_e^{(-)} \rightarrow \bar{\nu}_e^{(-)}$$

- ▶ MicroBooNE will test the MiniBooNE low-energy anomaly by measuring $\pi^0 \rightarrow 2\gamma$ background.

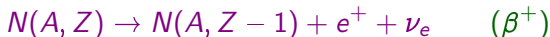
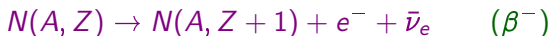
- ▶ ν_e disappearance: new SAGE Gallium source experiments with 2 spherical shells

[Gavrin et al, arXiv:1006.2103]

- ▶ CPT test: ν_e and $\bar{\nu}_e$ disappearance

- ▶ Beta-Beam experiments:

[Antusch, Fernandez-Martinez, PLB 665 (2008) 190, arXiv:0804.2820]

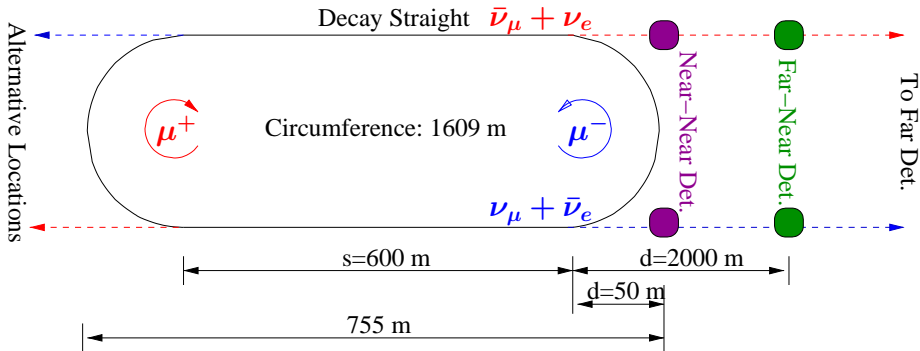


- ▶ Neutrino Factory experiments:

[Giunti, Laveder, Winter, PRD 80 (2009) 073005, arXiv:0907.5487]



Neutrino Factory



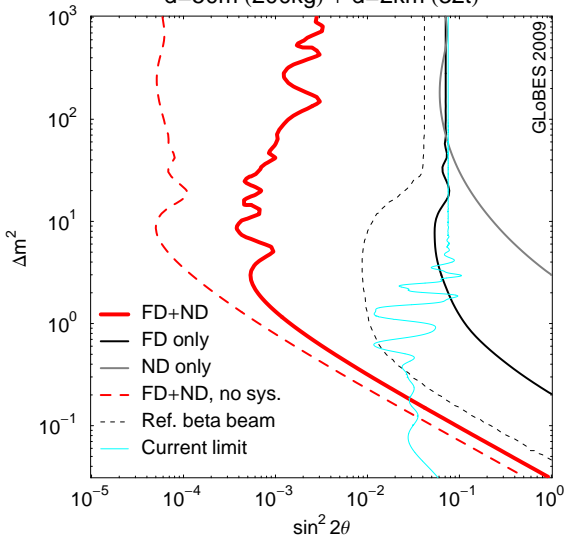
[Giunti, Laveder, Winter, PRD 80 (2009) 073005, arXiv:0907.5487]

Near Detectors: Scintillator or Iron Calorimeter
with perfect flavor identification

Systematic Uncertainties: Cross Section, Detector Normalization,
Energy Resolution and Calibration,
Backgrounds

ν_e Disappearance

d=50m (200kg) + d=2km (32t)



[Giunti, Laveder, Winter, PRD 80 (2009) 073005, arXiv:0907.5487]

- ▶ New ν_e and $\bar{\nu}_e$ radioactive source experiments with low-threshold neutrino elastic scattering detectors.



[Pallavicini, talk at BEYOND3NU]

[Ianni, Montanino, Scioscia, EPJC 8 (1999) 609, arXiv:hep-ex/9901012]

- ▶ LENS (Low Energy Neutrino Spectroscopy):

[Agarwalla, Raghavan, arXiv:1011.4509]



- ▶ Spherical Gaseous TPC:

[Vergados, Giomataris, Novikov, arXiv:1103.5307]

- ▶ Targets: ${}^{131}\text{Xe}$, ${}^{40}\text{Ar}$, ${}^{20}\text{Ne}$, ${}^4\text{He}$.

- ▶ Sources: ${}^{37}\text{Ar}$, ${}^{51}\text{Cr}$, ${}^{65}\text{Zn}$, ${}^{32}\text{P}$.

Conclusions

- Solar Neutrinos and KamLAND
- Atmospheric and LBL Oscillation Experiments
- Phenomenology of Three-Neutrino Mixing
- Absolute Scale of Neutrino Masses
- Anomalies Beyond Three-Neutrino Mixing
- **Conclusions**

Conclusions - Three-Neutrino Mixing

$\nu_e \rightarrow \nu_\mu, \nu_\tau$ with $\Delta m_{\text{SOL}}^2 \simeq 8.3 \times 10^{-5} \text{ eV}^2$ (SOL, KamLAND)

$\nu_\mu \rightarrow \nu_\tau$ with $\Delta m_{\text{ATM}}^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2$ (ATM, K2K, MINOS)



Bilarge 3ν -Mixing with $|U_{e3}|^2 \ll 1$ (CHOOZ)

β & $\beta\beta_{0\nu}$ Decay and Cosmology $\Rightarrow m_\nu \lesssim 1 \text{ eV}$

To Do

Theory: Why lepton mixing \neq quark mixing?

(Due to Majorana nature of ν 's?)

Why only $|U_{e3}|^2 \ll 1$?

Exp.: Measure $|U_{e3}| > 0 \Rightarrow$ CP viol., matter effects, mass hierarchy.

Find absolute mass scale.

Conclusions - Anomalies - 1

- ▶ Suggestive LSND and MiniBooNE agreement on SBL $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- ▶ Hint in favor of sterile neutrinos is compatible with cosmological data, but mass is limited
- ▶ Two experimental tensions:
 - ▶ LSND and MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ vs MiniBooNE $\nu_\mu \rightarrow \nu_e$ (CP violation?)
 - ▶ LSND and MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ vs $\bar{\nu}_e$ and ν_μ disappearance limits
- ▶ CPT-invariant 3+1 Four-Neutrino Mixing is strongly disfavored (no CP violation and tension between appearance and disappearance)
- ▶ 3+2 can explain CP violation and reduce tension between appearance and disappearance with New Reactor $\bar{\nu}_e$ Fluxes
- ▶ 3+1+NSI has CP violation and reduced appearance-disappearance tension
- ▶ CPT-violating 3+1 Mixing \implies testable large SBL $\bar{\nu}_\mu$ disappearance

Conclusions - Anomalies - 2

- ▶ Interesting possible agreement of
 - ▶ Gallium Anomaly (SBL ν_e disappearance)
 - ▶ Reactor Anomaly (SBL $\bar{\nu}_e$ disappearance)
- ▶ Testable Predictions:
 - ▶ $m_\beta \sim 0.12 - 0.71 \text{ eV} \quad (2\sigma)$
 - ▶ $m_{\beta\beta} \sim 0.011 - 0.15 \text{ eV} \quad (2\sigma)$
- ▶ Exciting experimental results in favor of sterile neutrinos.
- ▶ More work to do because interpretation is not clear:
 - ▶ Explanation of all data needs at least two new physical effects.
 - ▶ Without CPT violation tensions do not disappear completely.
 - ▶ Possible that some experiments are giving misleading information.
- ▶ New short-baseline neutrino oscillation experiments are needed!