A New Fit to Solar Neutrinos Using Extra Dimensions

David O. Caldwell

University of California Santa Barbara

Relevance of a new analysis of LSND data

Likely 4-ν mass-mixing scheme (adding a ν_s)

Support for the scheme from the r process

Need for extra dimensions for solar $\nu_e \to \nu_s$

Some implications of having ν_s in extra dimensions

New LSND Analysis

Likelihood based on light amplitudes and arrival times

Fit to position, energy, direction, track length, % Č rad.

Formerly used input information separately

Improved position resolution = better accidental γ rejection

Old R>30 vs. new R>10 ($\bar{\nu}_e p \rightarrow e^+ n$, $np \rightarrow \gamma d$)

Correlated γ efficiency: from 23% to 40%

Accidental background drops from 0.6% to 0.23%

Results for R>10

86 beam-on events, 36.9 beam-off, 16.9 ν background

Excess = 32.2 ± 9.4

Probability 36.9+16.9=53.8 fluctuates to 86 is $< 1 \times 10^{-4}$

Implications

LSND results require 4 neutrinos (i.e., one sterile ν_s)

$\nu_\mu \to \nu_\tau$ for the atmospheric ν_e/ν_μ anomaly ($\Delta m^2 \sim 10^{-3} eV^2$)

$\nu_e \to \nu_s$ for the solar ν_e deficit ($\Delta m^2 < 10^{-5} eV^2$)

$\nu_\mu \to \nu_e$ with $0.2 \leq \Delta m^2 \leq 10\ eV^2$ from LSND

Scheme suggested ~8 years ago, prior to LSND D.O.C Moriond

For solar, atmospheric, hot dark matter ($\nu_\mu + \nu_\tau$)

Given theoretical basis: D.O.C.+Mohapatra; Peltoniemi+Valle

4-ν Scheme Supported by Supernova Nucleosynthesis

Problems with r-process heavy-element production

Models give too few neutrons (need ~10^2/"Fe" seed)

Fatal α production inside r region ($p, n \to \alpha$, $\nu_e n \to e^- p$, etc.)

Solved by two neutrino level crossings D.O.C., Fuller, Qian

Inner: $\nu_{\mu,\tau}$ (maximally mixed) $\to \nu_s$ (near $V_{\mu,\tau} \to 0$)

Outer: $\nu_e \to \nu_{\mu,\tau}$ (LSND MSW density), not $\nu_{\mu,\tau} \to \nu_e$

Result in r region: $1/4\,\nu_\mu$, $1/4\,\nu_\tau$, $1/2\,\nu_s$, and no ν_e

Despite needed huge ν_e flux at smaller radius

$\bar{\nu}_e$ unaffected, so $\bar{\nu}_e p \to e^+ n$ enriches r region

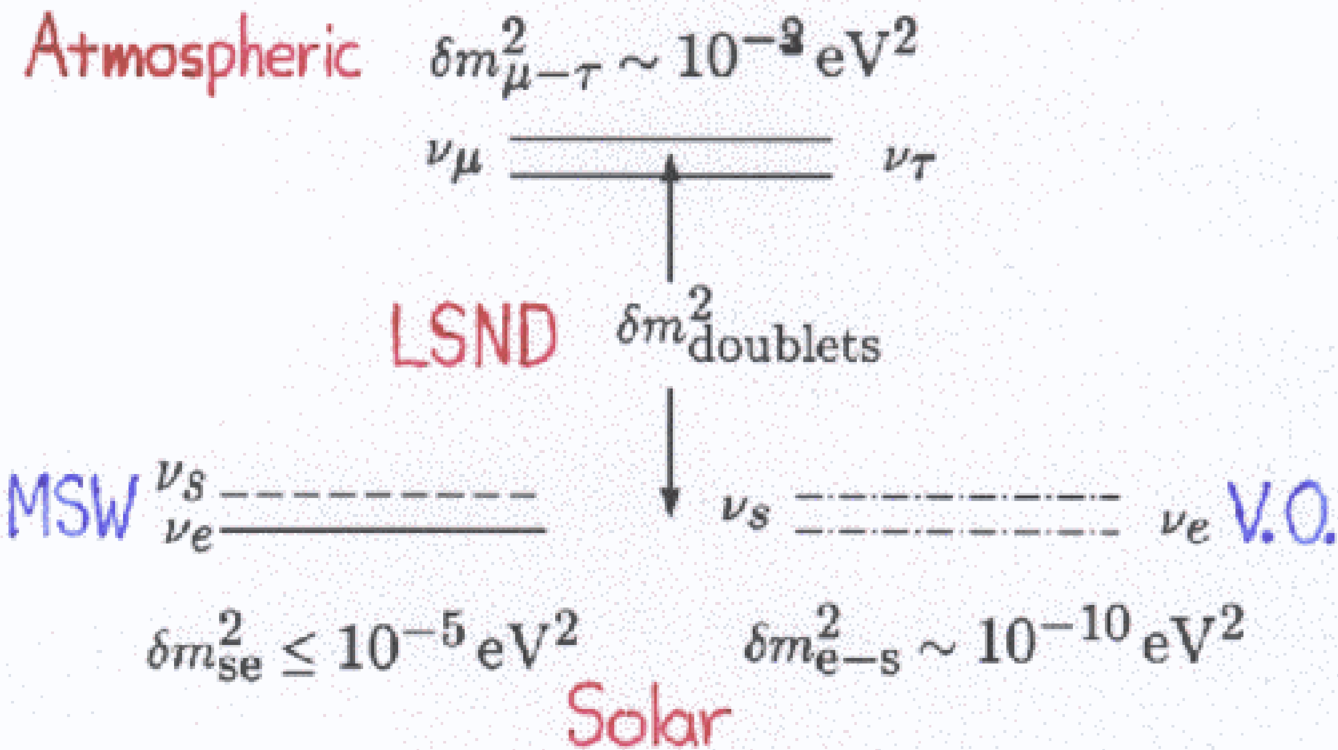
Neutrino properties required

At least one light sterile neutrino

ν_μ, ν_τ maximally mixed (as atmospheric data shows)

ν_e, ν_μ mixing $> 10^{-4}$

$\Delta m^2_{e\mu} > 1\,\mathrm{eV}^2$ (keeps level crossings in correct order)



Atmospheric
$\delta m^2_{\mu-\tau} \sim 10^{-3}\,\mathrm{eV}^2$
ν_μ
ν_τ
LSND
$\delta m^2_{\mathrm{doublets}}$
MSW
ν_s
ν_e
ν_s
ν_e
V.O.
$\delta m^2_{\mathrm{se}} \leq 10^{-5}\,\mathrm{eV}^2$
$\delta m^2_{\mathrm{e-s}} \sim 10^{-10}\,\mathrm{eV}^2$
Solar

Relevance of the Solar Neutrino Deficit

Measurements to test MSW or vacuum oscillations (V.O.)

- Rates: GALLEX+SAGE (>0.23 MeV), Cl (>0.81), Super-K (>5.5)
- Energy spectrum in Super-K (nothing fits well)
- Day-night (MSW only, but a 1σ effect)
- Seasonal (V.O. only, but slight or none)

Nothing fits well for $\nu_e \to \nu_\mu$, and $\nu_e \to \nu_s$ is worse

- MSW (small-∠ only) fair for rates, can't fit spectrum
- V.O. fair for spectrum, can't fit rates

Invoking Extra Dimensions

Sterile neutrinos

Prejudice against: hard to make light, mix with other νs

Models with large extra dimensions solve the problems

For simplicity, take one large extra dimension of size R

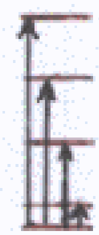
ν_s is a bulk state with active ν's on a brane

ν_s has Kaluza-Klein (K-K) higher mass states ($m_n \approx \frac{n}{R}$)

Required phenomenology

Zero mode of ν_s split slightly from ν_e to give V.O.

Spacing of K-K states (gravity limits) give ν_e MSW



Model from R.N. Mohapatra

After EW symmetry breaking ν_s is a Dirac ν of $\sim 10^{-5}$ eV

Add 2 Higgs singlets to get ν masses radiatively (2 loops)

Dirac ν_s splits giving Majorana ν_e, ν_s (doubles K-K) and V.O.

Radiative effects give Majorana mass to ν_μ, ν_τ (atmos., LSND)

Confronting the Data

Mixing: $\cos\theta = 1/N$, where $N^2 = 1 + \pi^2 (m_0 R)^2 + (\frac{m_n}{m_0})^2$

V.O. ($n=0$): $m_0 R \ll 1$, $N^2 \approx 2$, $\cos\theta \approx 1/\sqrt{2}$, $\theta \approx \frac{\pi}{4}$ (maximal mixing)

MSW ($n \geq 1$): $N^2 \approx 1 + (\frac{n}{m_0 R})^2$, $\cos\theta \approx \frac{m_0 R}{n} \approx 10^{-2}/n$ (very small)

Fitting to 3 rates neglecting errors in fluxes (S.J. Yellin)

SAGE+GALLEX+GNO: ν_e survival probability $= 0.579 \pm 0.039$

Cl (Homestake): 0.332 ± 0.030

Super-Kamiokande: 0.465 ± 0.015

Results: 0.533, 0.386, 0.460

Some consequences

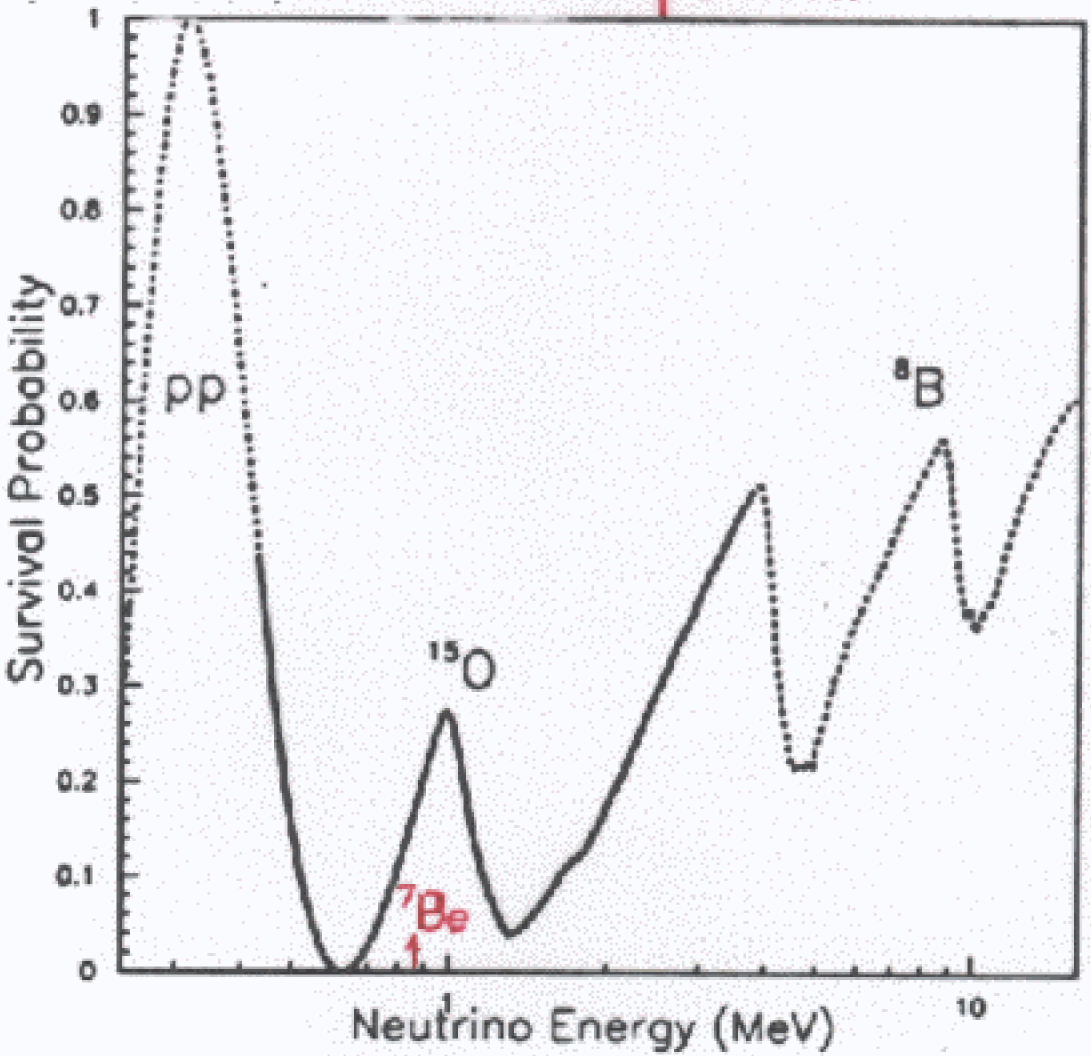
$\Delta m^2_{V.O.} = 0.53 \times 10^{-11}\,eV^2$, $\sin^2 2\theta_{MSW_1} = 3.5 \times 10^{-4}$, $m_0 \approx m_{\nu_e} = 3 \times 10^{-5}\,eV$

All very small: no $\beta\beta$, little seasonal or day-night effects

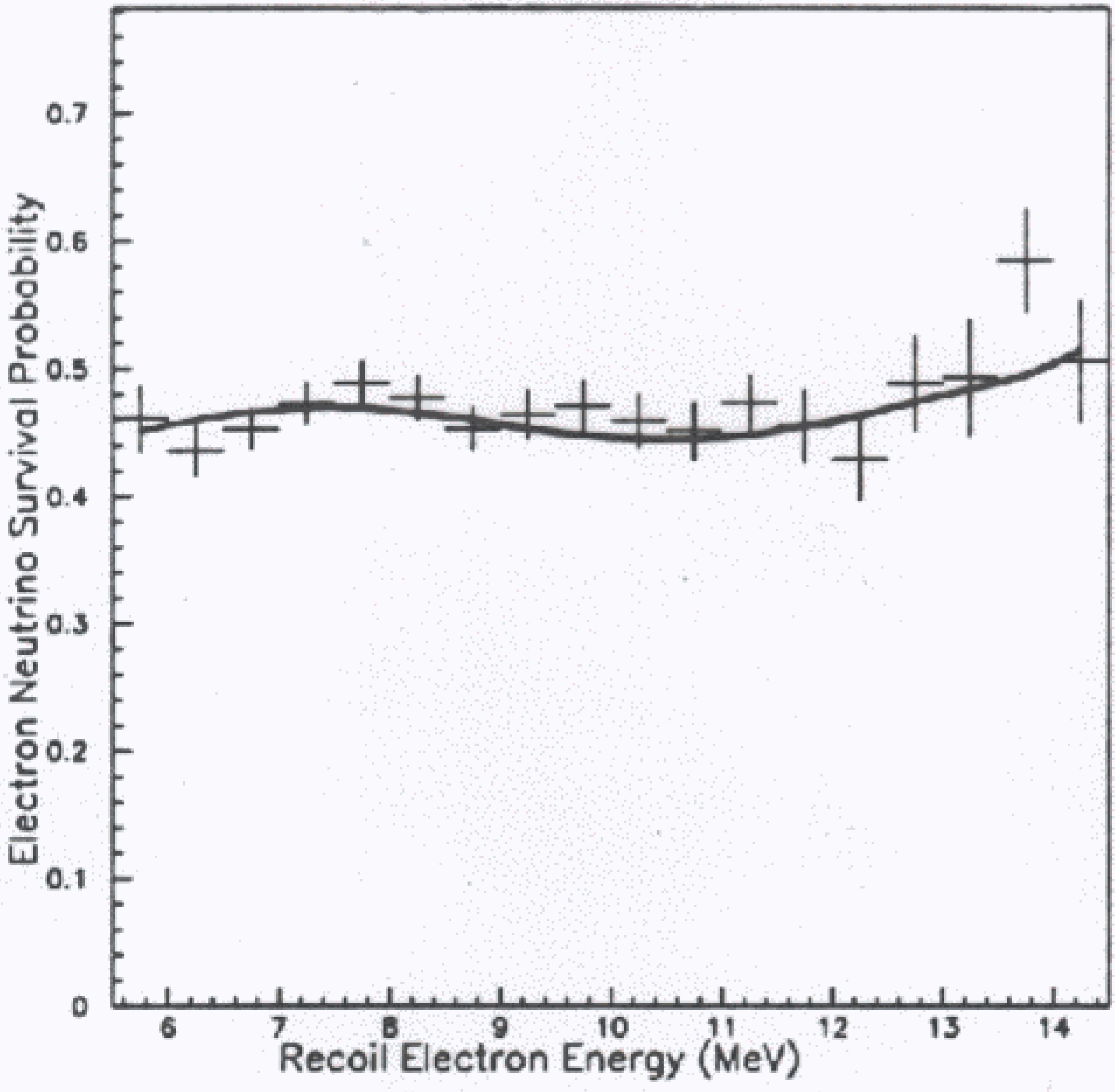
Avoids supernova, BB nucleosynthesis bounds (1 K-K tower; low m_{ν_e})

$R = 58\,\mu m$, so gravity experiments can test it

Predicted Spectrum



1117-Day Super-Kamiokande Data



This not a fit to data!

Implications of Bulk Sterile Neutrinos

Cosmic rays beyond the G-Z-K cut-off

- ν with large σ at high E would do, but see low-E effects
- $\nu \to \nu_s$ K-K states avoid this limit by density of states

Dark matter (Abazajian, Fuller, Patel, ...)

- K-K states from reheating after inflation
- Single K-K tower based on a very small mass (10^{-5}eV)
- Not in thermal equilibrium—avoids nucleosynthesis limit
- Solar parameters give $\Omega_m \sim 0.5$-1 (depends on reheat T)
- Dark matter: little hot, ~½ warm, ~½ cold

Supernovae

- Two-level-crossing r process still OK
- Not such a limit on extra-D models as some claimed
- Behavior of ν's in core more complex
- Reconversion behind the shock may aid blow-up

Conclusions

LSND's new analysis strengthens $\bar{\nu}_\mu \to \bar{\nu}_e$ positive result

4-ν scheme satisfies all ν-oscillation, r-process input

Large extra dimension needed for solar $\nu_e \to \nu_s$

If so, many implications: dark matter, cosmic rays, supernova

SNO will soon show if this correct!