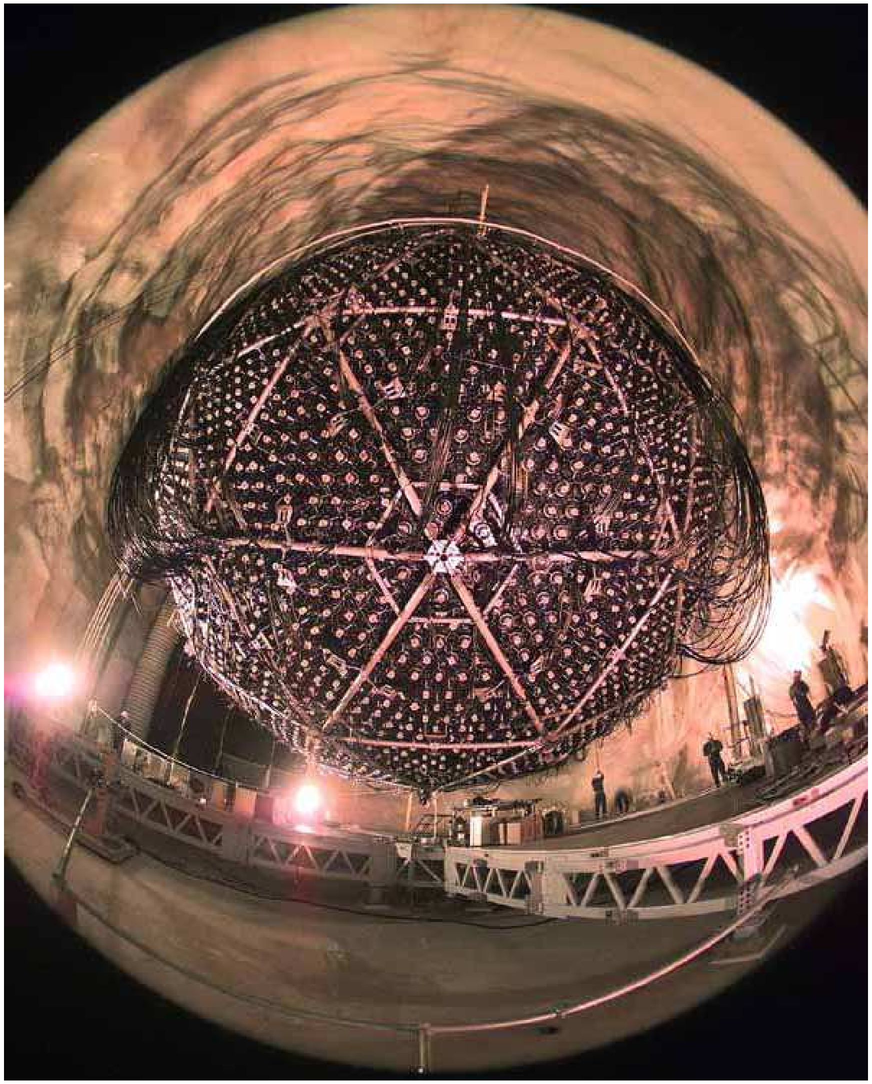
Neutrino Physics: *Non-Accelerator Results*



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XXVII Physics In Collision 2007

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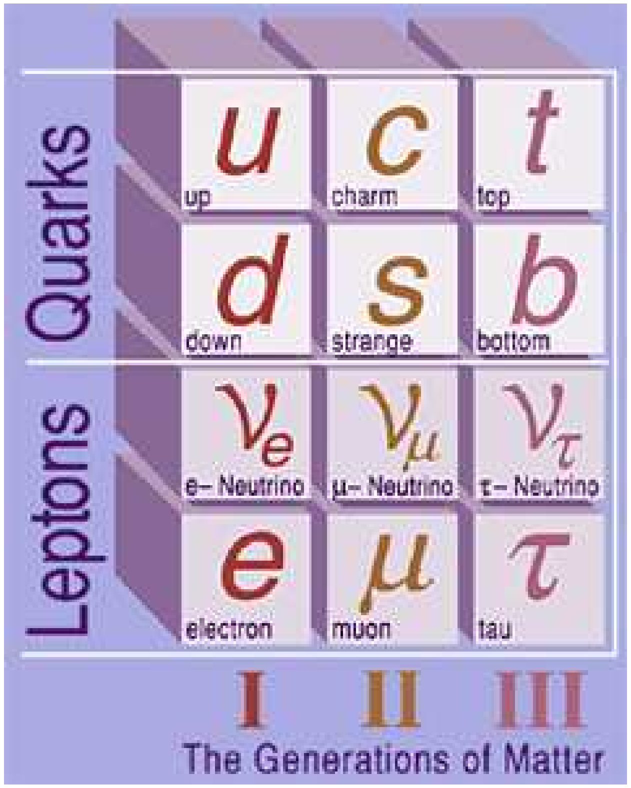
Outline

1. Neutrinos In The Standard Model
2. Neutrino Mixing And Oscillation
3. Atmospheric Neutrino Oscillations
4. The Solar Neutrino Problem, With Solution
5. Reactor Neutrino Results
6. Future Prospects

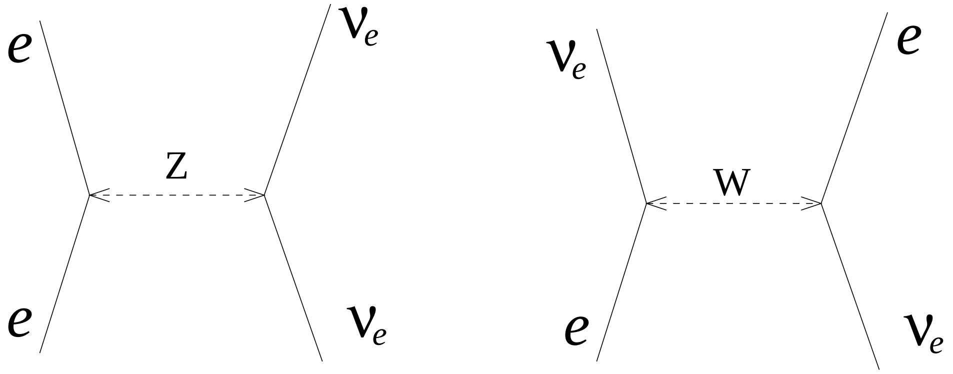
Neutrinos in the Standard Model



In the Standard Model, $m_\nu \equiv 0$.

(Current limit is $\sum m_i <\sim 0.6$ eV).

Neutrinos are many orders of magnitude lighter than the other fermions.

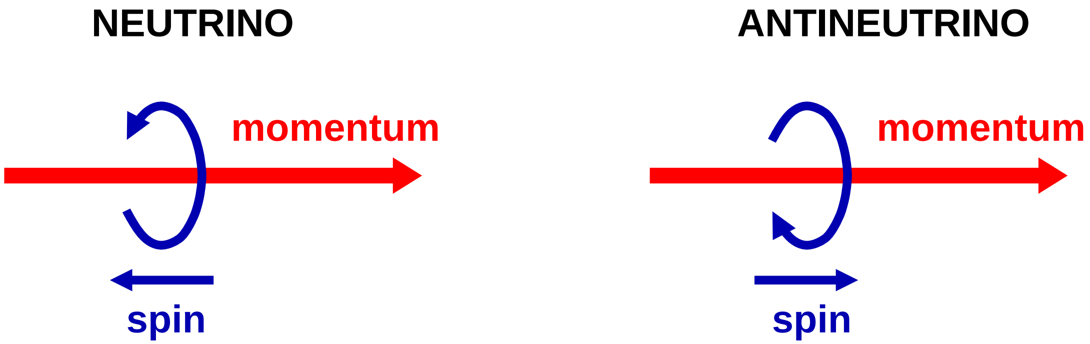


Only weak interactions — carried by very heavy W, Z particles with short ranges

Flavour universality: identical couplings to all generations

Flavour conservation at all vertices: “electron-ness”, “mu-ness”, & “tau-ness” are conserved quantities (although not required by any symmetry of Lagrangian)

The Left and the Right of the Matter



Weak interactions only couple to left-handed ν's, or right-handed $\bar{\nu}$'s

This is a pure V-A interaction (maximally parity violating). Weak current has the form:

$$j_\mu = \bar{\psi}\gamma_\mu(1-\gamma_5)\psi$$

Right-handed ν's either don't exist, or are sterile (don't interact).

A plausible, but wrong, argument ...

1. Ockham's Razor: the simplest solution is if right-handed ν's don't exist.
2. In Standard Model, mass couples left-handed and right-handed states.
3. Therefore, to avoid right-handed states, neutrinos should have no mass.

Neutrino Flavour Mixing

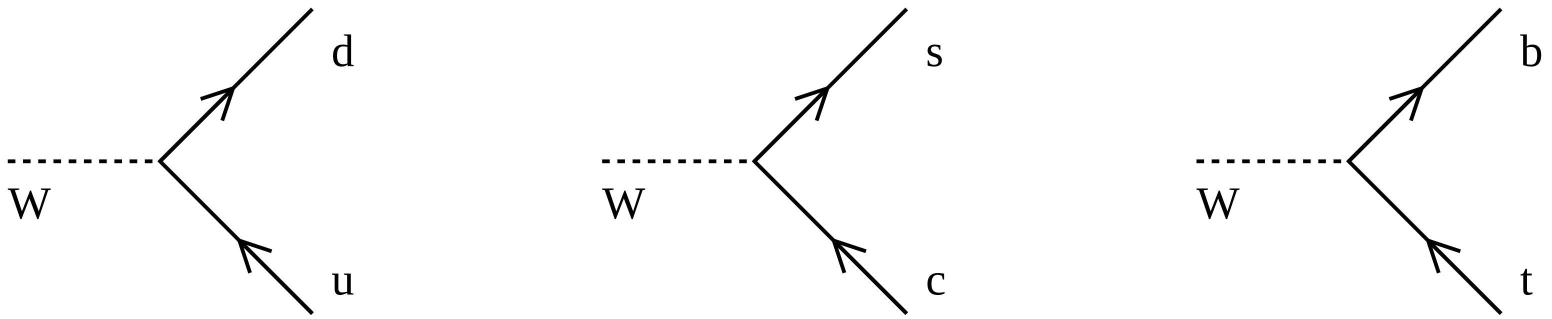
In Standard Model, neutrinos are rather boring ... they have no mass, and only seem to be there to conserve lepton number, flavour number, and energy/momenta/spin.

In 1962, Maki, Nakagawa, and Sakata proposed, on the basis of *zero* experimental evidence, a new phenomenon called neutrino oscillation.

To understand what led MNS to this, let's look at quark mixing first.

Weak Interactions with Quarks

The simple version: W particle couples $u \leftrightarrow d$, $c \leftrightarrow s$, $t \leftrightarrow b$,



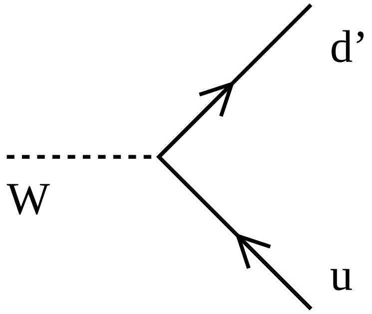
But this can’t be complete, since we see weak decays such as:

$$\Lambda(uds) \rightarrow p(uud) + \pi^-(d\bar{u})$$

Somehow the strange quark in the Λ gets turned into an up quark!

Quark Flavour Mixing

In reality, W particle couplings mix quark generations:



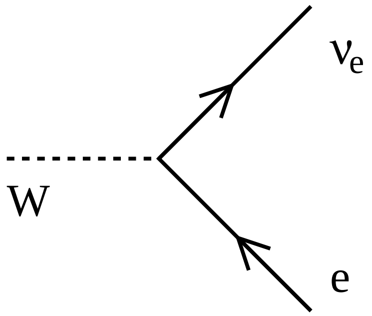
We say that flavour eigenstates (eg. d,s,b) are *rotated* with respect to weak eigenstates (d’,s’,b’)

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

This allows generation-mixing decays such as $\Lambda(uds) \rightarrow p\pi^-$

Neutrino Mixing



Since ν's have only weak interactions, flavour eigenstates are defined as those states that couple to W. So it's not sensible to talk of rotation between weak eigenstate and flavour eigenstates.

But what if the flavour eigenstates are rotated relative to the *mass* eigenstates (eigenstates of Hamiltonian with well-defined mass)?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

How does superposition of mass eigenstates evolve in vacuum?

$$\begin{aligned} |\nu_e\rangle &= \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle \\ |\nu_\mu\rangle &= -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle \end{aligned}$$

Each term evolves with a phase factor of $e^{i(px-Et)}$

If $m_1 \neq m_2$, then arguments of exponential will be different! For example, if we consider p to be fixed, then

$$E = \sqrt{p^2+m^2} = p\sqrt{1+m^2/p^2} \approx p + m^2/(2p)$$

As neutrino propagates, a phase difference develops between terms!

$$|\nu(t)\rangle \propto \cos\theta\,|\nu_1\rangle + e^{i\phi}\sin\theta\,|\nu_2\rangle$$

with

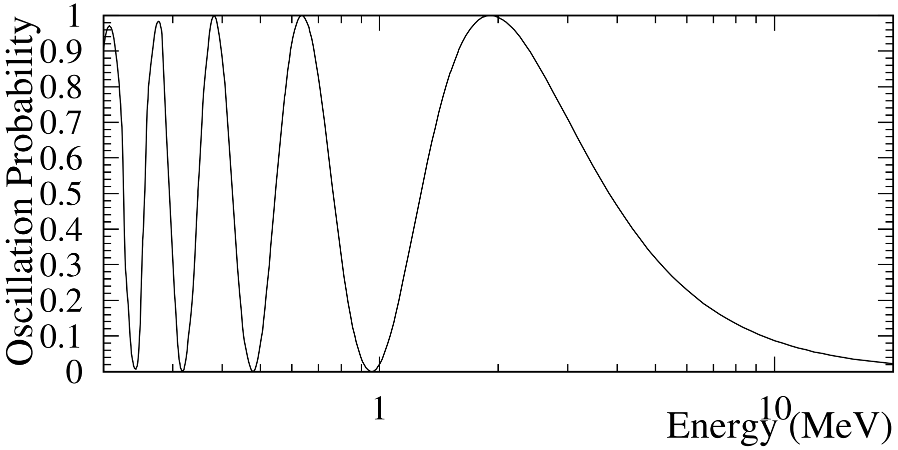
$$\phi = \left(\frac{m_1^2}{2p} - \frac{m_2^2}{2p}\right)t$$

Neutrino Oscillation

Net result: at some later time, $|\nu(t)\rangle \neq |\nu_e\rangle$.

Probability that the original ν_e is detected as a ν_μ at some later time:

$$P(\nu_e \rightarrow \nu_\mu) = |\langle\nu_\mu|\nu(t)\rangle|^2 = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



θ = neutrino mixing angle

Δm^2 = $m_1^2 - m_2^2$ (in eV^2)

L = distance ν has travelled (in km)

E = neutrino energy (in GeV)

Neutrino oscillation:

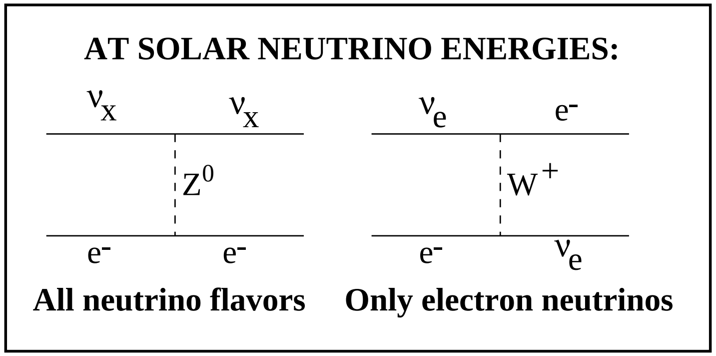
- requires at least one non-zero neutrino mass
- requires non-zero mixing elements
- results from the QM of the propagation, *not* from an interaction

Matter Effects On Neutrino Oscillation

Surprisingly the oscillation formula can be dramatically altered in matter!

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\begin{pmatrix}-\frac{\Delta m^2}{4E}\cos 2\theta+\sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta\\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

The relevant process is forward scattering, in which no momentum is exchanged. In matter, ν_e's have a different forward scattering amplitude than the other flavours:



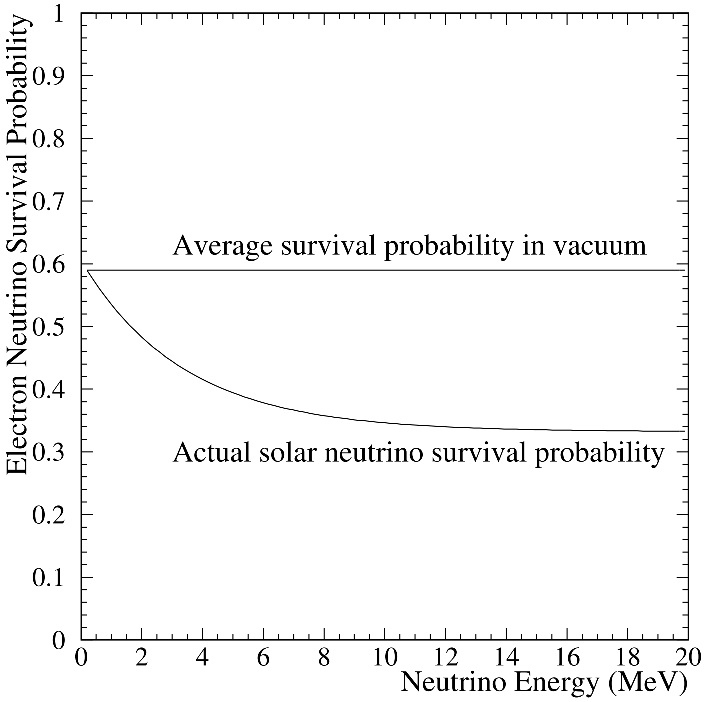
AT SOLAR NEUTRINO ENERGIES:

All neutrino flavors **Only electron neutrinos**

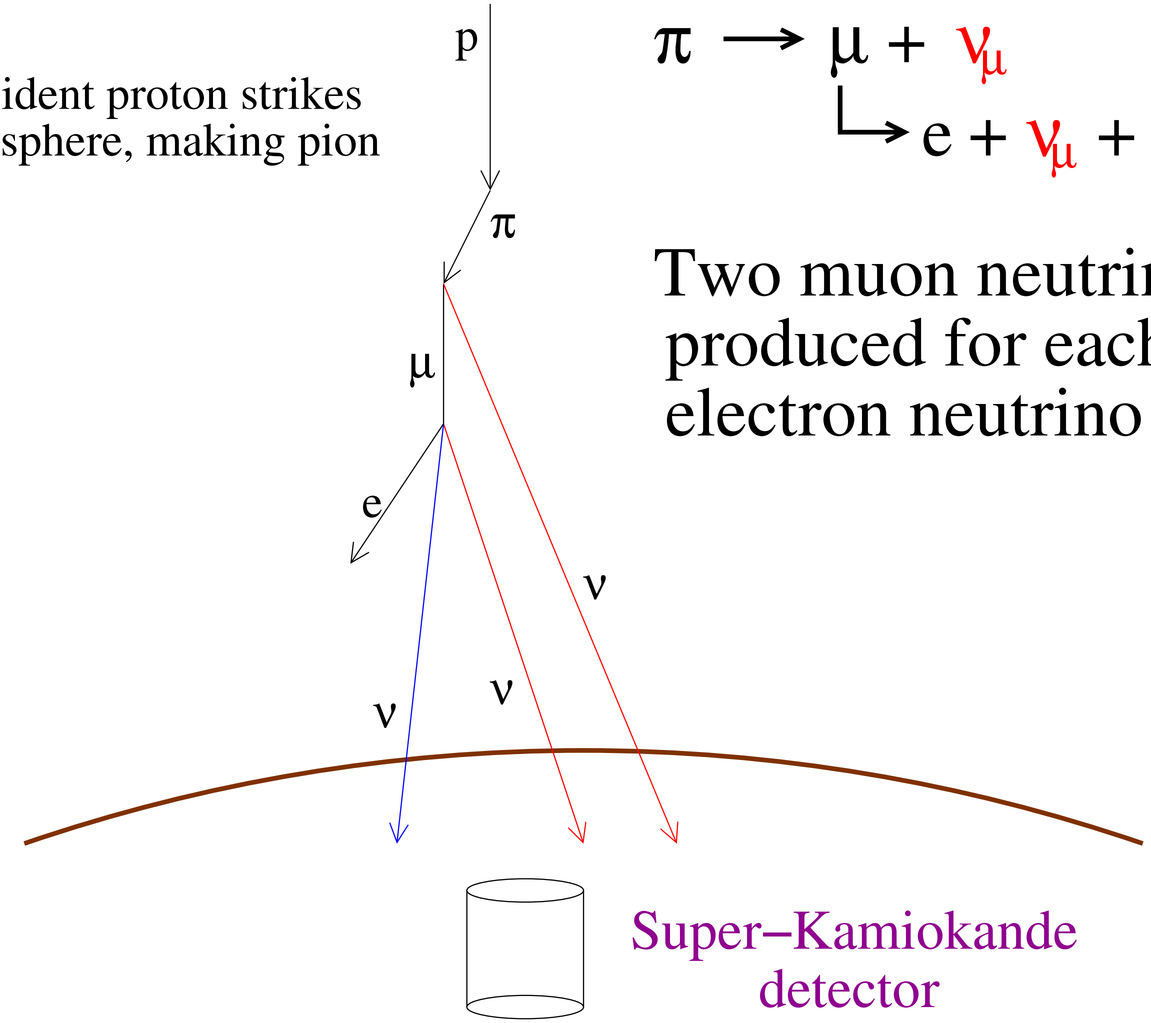
This produces a matter-induced potential that is different for ν_e. Effectively ν_e's have a different "index of refraction" in matter.

The size of the potential is proportional to the electron density N_e.

For solar ν's, matter effects are dominant.



Atmospheric Neutrinos



Incident proton strikes
atmosphere, making pion

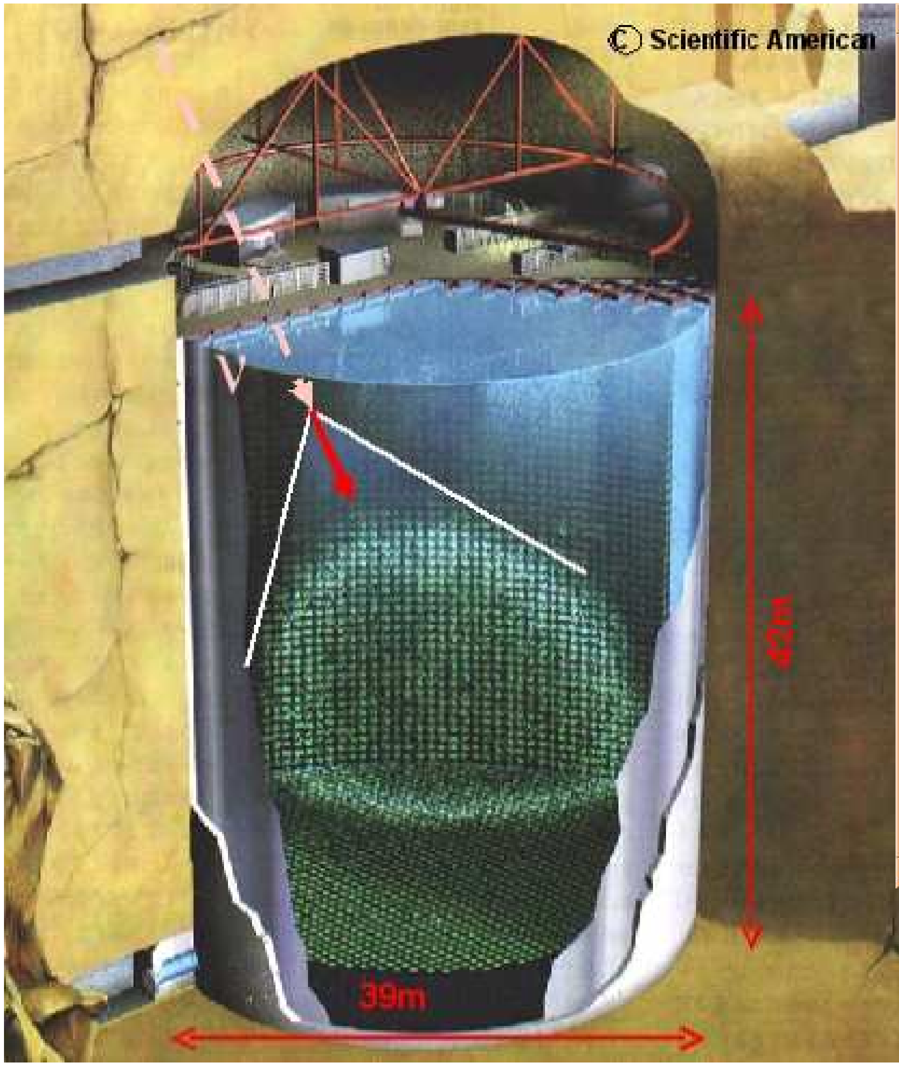
$$\pi \longrightarrow \mu + \nu_\mu$$

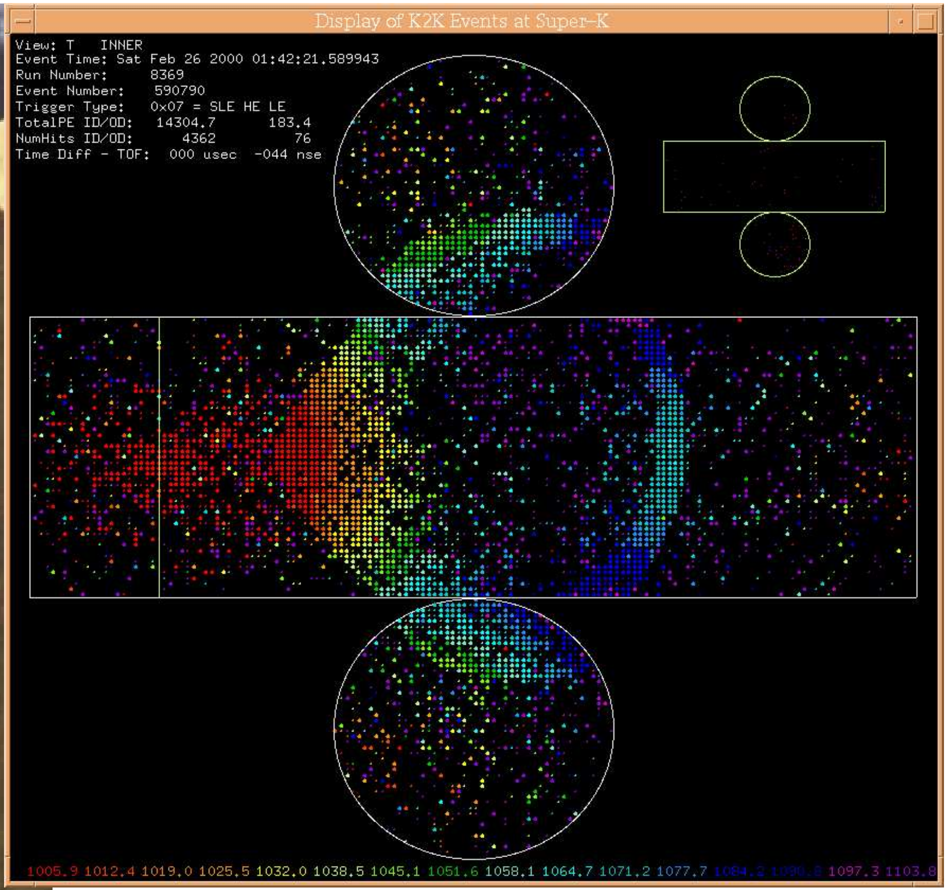
$$\qquad \hookrightarrow e + \nu_\mu + \nu_e$$

Two muon neutrinos produced for each electron neutrino!

Super–Kamiokande
detector

Super-Kamiokande





```
View: T   INNER
Event Time: Sat Feb 26 2000 01:42:21.589943
Run Number:      8369
Event Number:     590790
Trigger Type:    0x07 = SLE HE LE
TotalPE ID/OD:    14304.7       183.4
NumHits ID/OD:       4362         76
Time Diff - TOF:   000 usec  -044 nse
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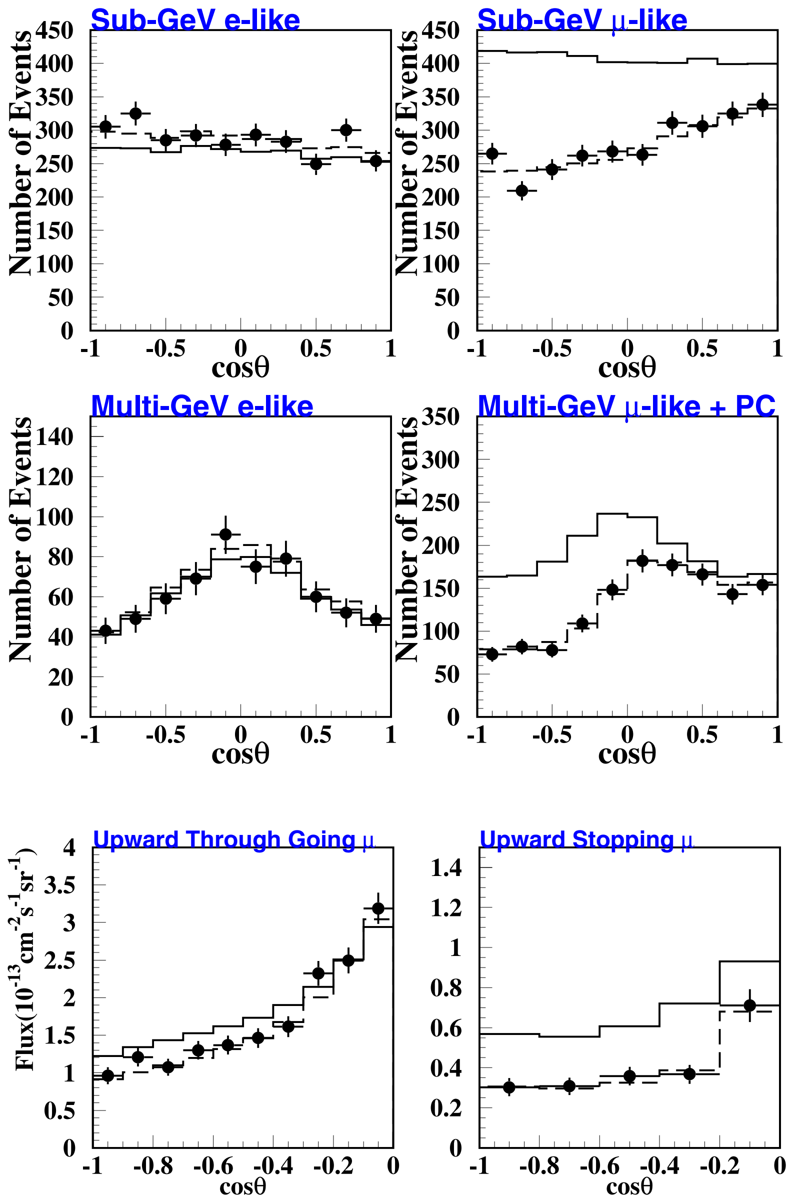
50 kton total mass

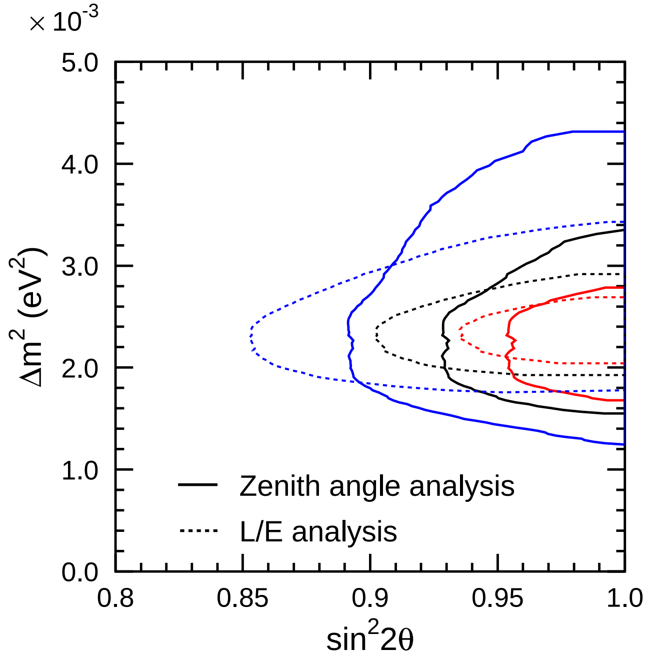
11K PMTs, + outward-looking

veto tubes

1 km overburden

Super-Kamiokande Atmospheric ν Results





PRD 71, 112005 (2005)

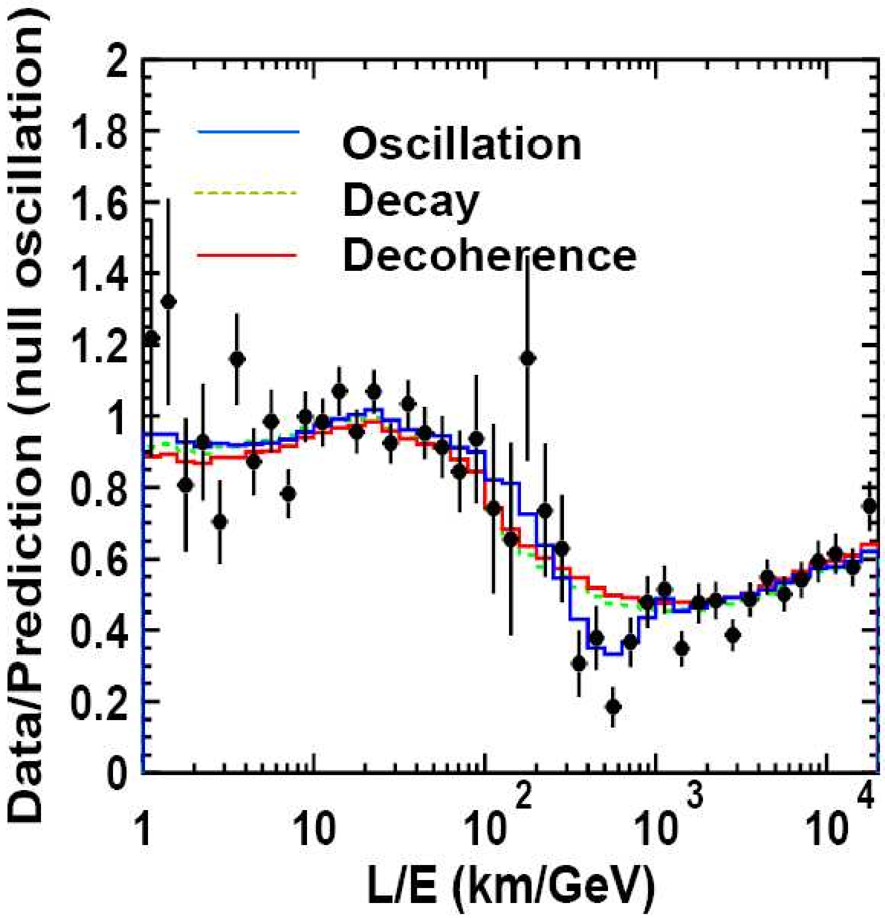
Super-K sees suppression of ν_μ flux at large zenith angles (distances).

ν_e flux is unaffected.

Looks to be $\nu_\mu \longrightarrow \nu_\tau$ oscillations

Super-K provided first clear evidence for neutrino oscillations (1998)!

Super-Kamiokande: Evidence for oscillatory signature



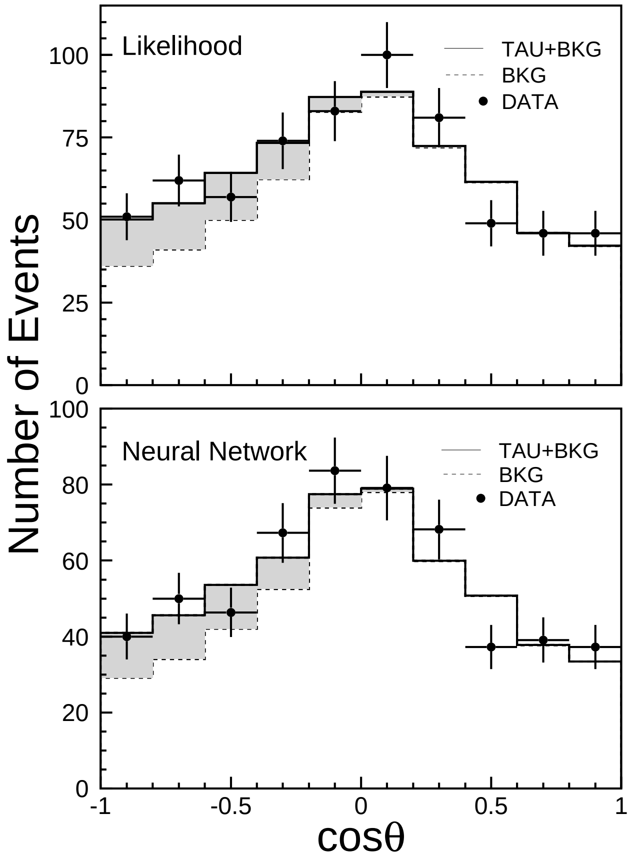
A subset of well-reconstructed events is used to do an L/E analysis.

Dip at the first oscillation minimum is a signature of oscillation .

Alternate models of neutrino decay, decoherence ruled out at $\sim 5\sigma$ level.

Taus or Steriles?

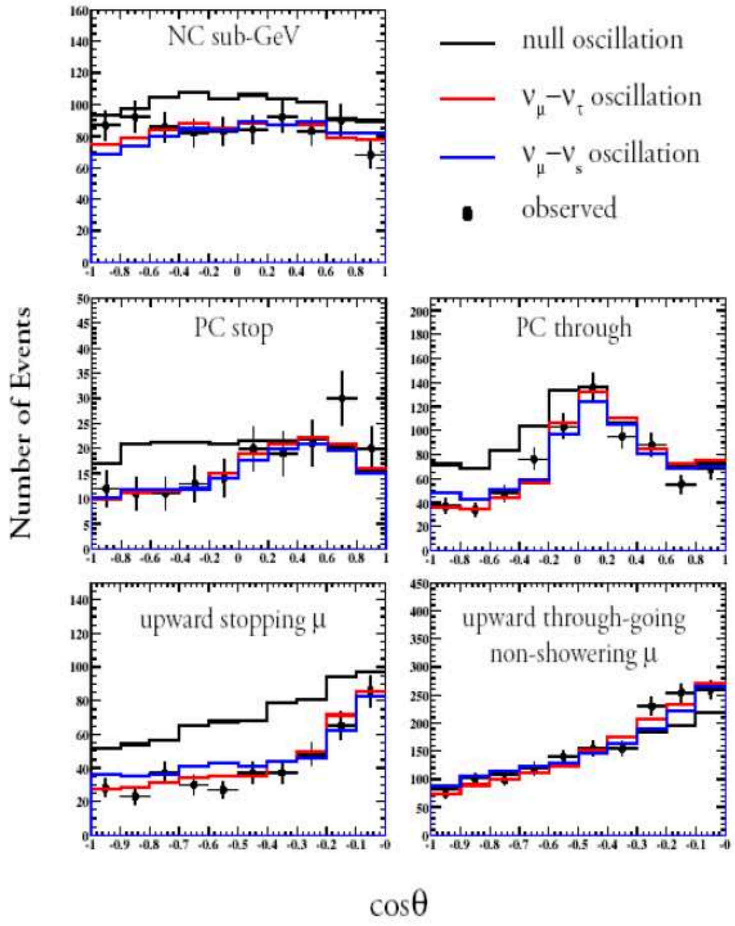
ν_τ search at Super-K



Hypothesis of no ν_τ appearance disfavored by 2.4σ

PRL 97, 171801 (2006)

$\nu_\mu \rightarrow \nu_{sterile}$? Different angular distribution due to matter effects.



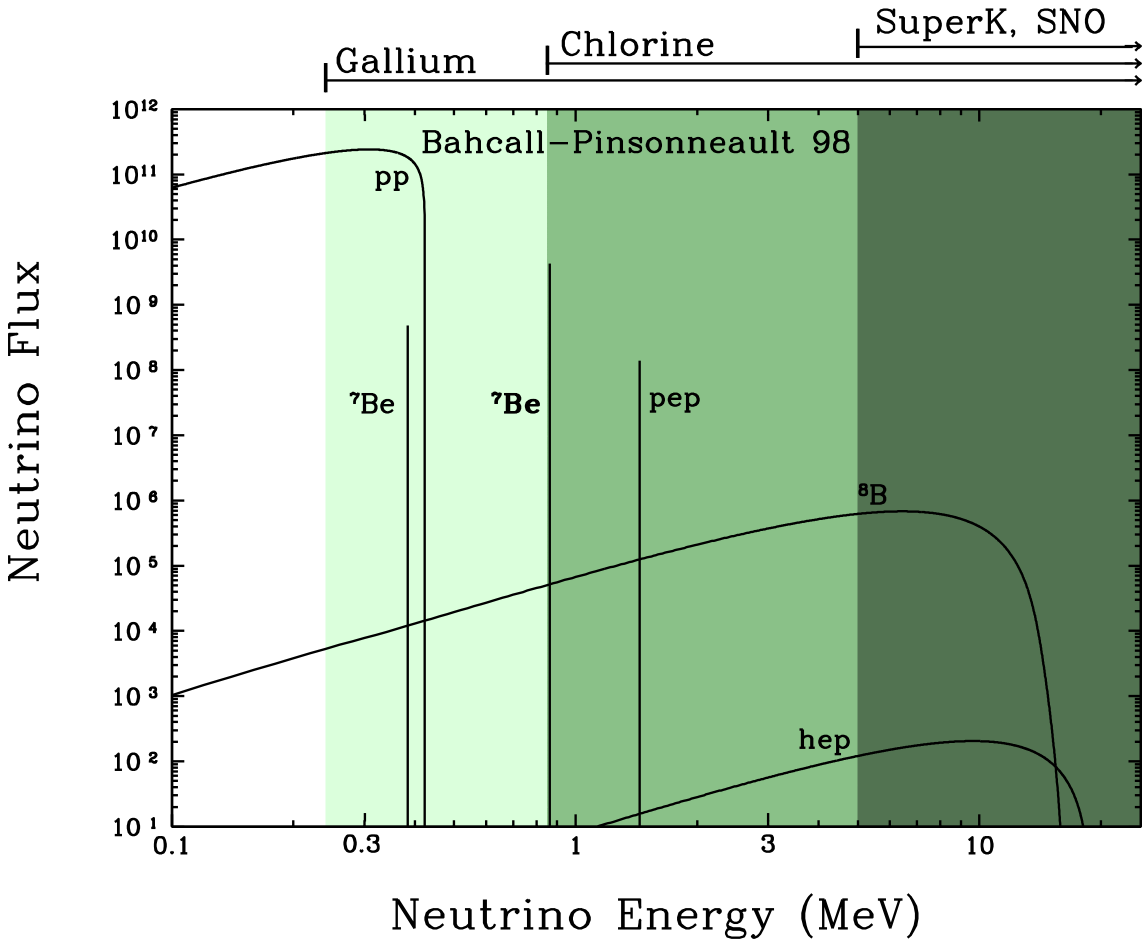
Best fit: no sterile component

Purely $\nu_\mu \rightarrow \nu_{sterile}$ ruled out at 7σ

Solar Neutrinos

The Sun is an intense source of MeV neutrinos!

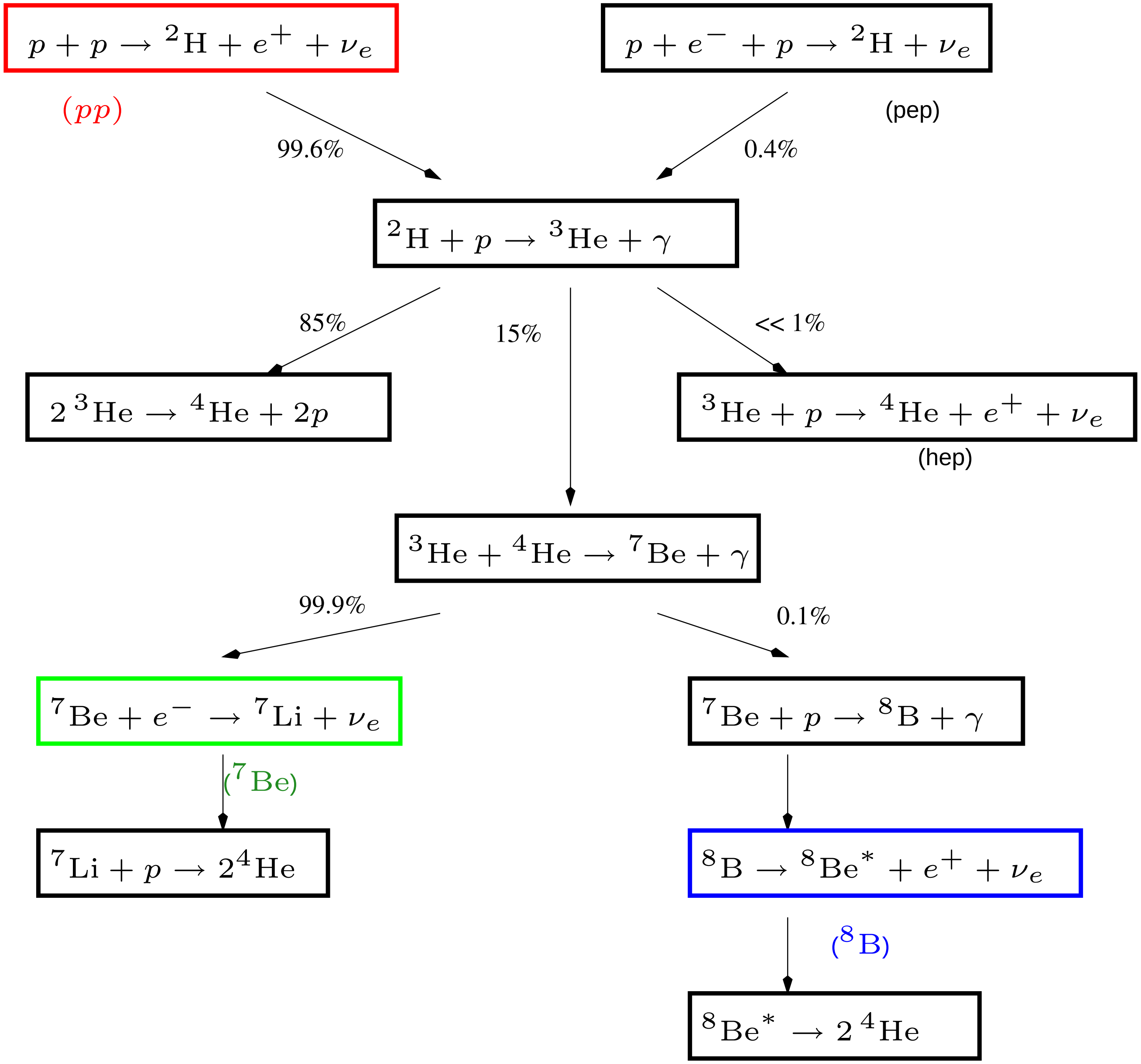
$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e + 26.731\ \text{MeV}$$



Shape of Spectra Determined By Nuclear Physics.

Solar Models Only Affect Normalization.

The pp Chain



$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

(pp)

99.6%

$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$

(pep)

0.4%

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

85%

15%

<< 1%

$2\,{}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

(hep)

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

99.9%

0.1%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

(${}^7\mathrm{Be}$)

${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$

${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$

(${}^8\mathrm{B}$)

${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

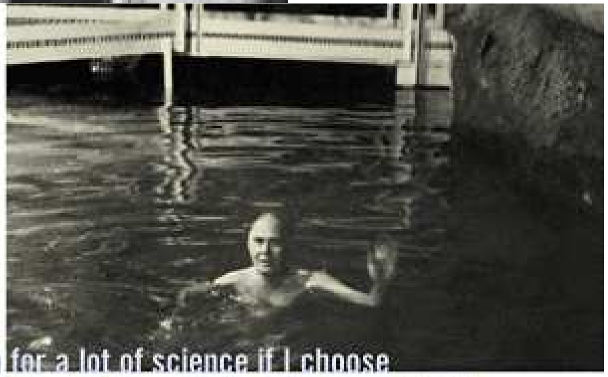
The Pioneers

The ^{37}Cl experiment started in the 1960's

Ray Davis and John Bahcall with the tetrachloroethylene tank.

100,000 gallons of cleaning fluid!

$$\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$$



“There's room for a lot of science if I choose this route and just start doing things.”

A setback ...

Predicted rate: $7.6^{+1.3}_{-1.1}$ SNU's

Measured rate: 2.56 ± 0.23 SNU's

Most people reacted in two ways ...

- Experiment must be wrong. No one can look for 50 Ar atoms in 600 tons of cleaning fluid and expect to find them all!
- Theory must be wrong. The solar models are too complicated to take seriously. The flux changes with solar temperature by T^{25}. Even a tiny mistake could change fluxes greatly!

Ray Davis checked and rechecked his experiment. John Bahcall refined astrophysical calculations. Both stuck to their guns.

Others began planning new experiments ...

Super-Kamiokande Solar Neutrino results

$$\nu_x \; + \; e^- \rightarrow \nu_x \; + \; e^-$$

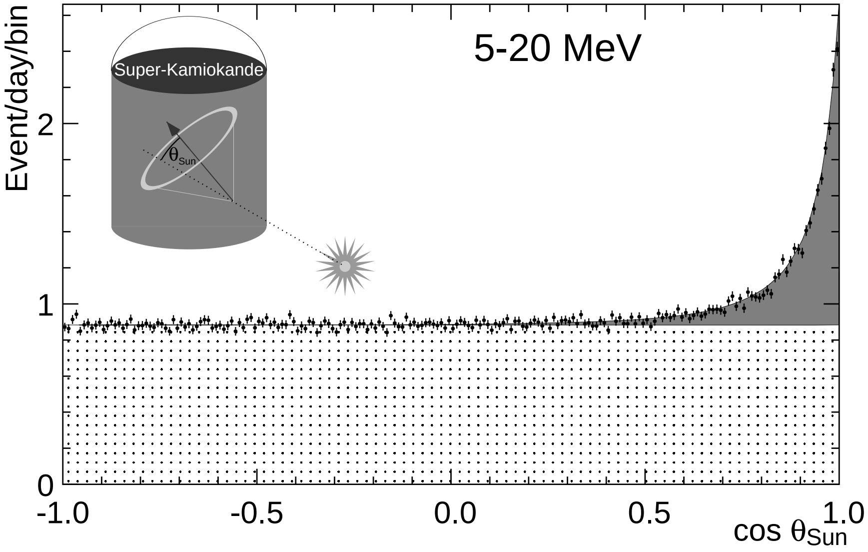
Rate $\propto \phi(\nu_e) + \frac{1}{6}\phi(\nu_{\mu\tau})$

$$\phi = 2.35 \pm 0.02 \pm 0.08 \times 10^6 \; \nu\text{/cm}^2\text{/s}$$

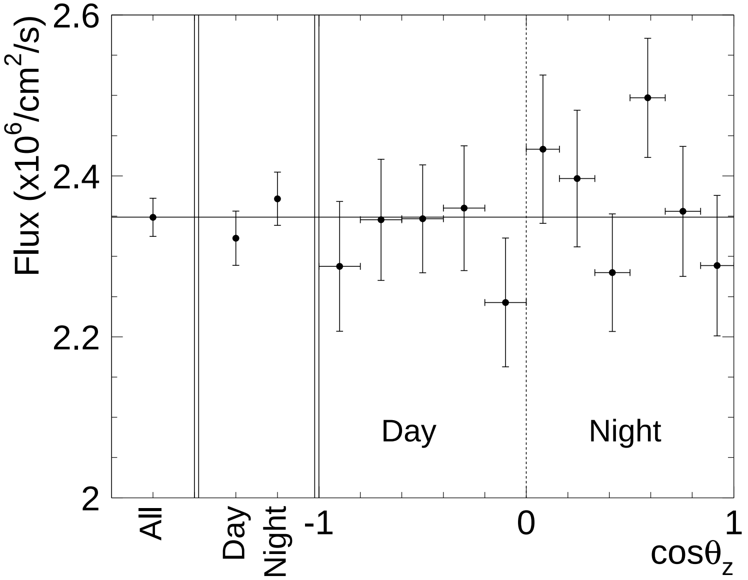
$$\phi_{SSM} = 5.69 \pm 0.91 \times 10^6 \; \nu\text{/cm}^2\text{/s}$$

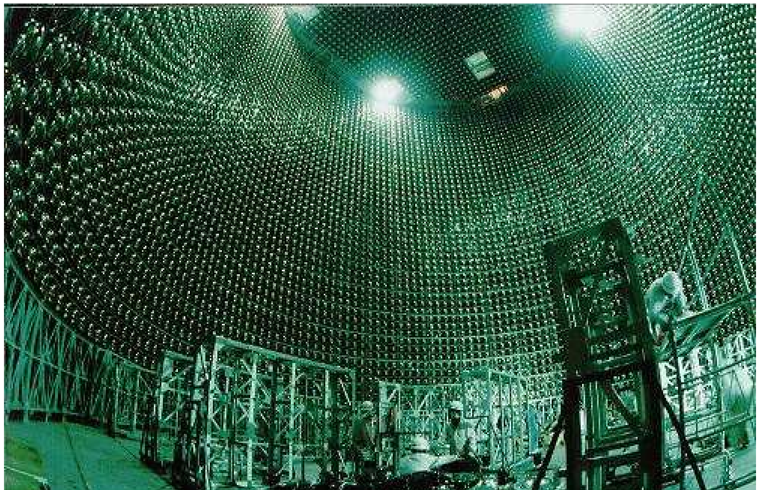
(PRD 73 (2006) 112001)

Clear directional ν signal from Sun!



No day-night variations (matter effects) or spectral distortions seen—could simply be seeing flux suppression.

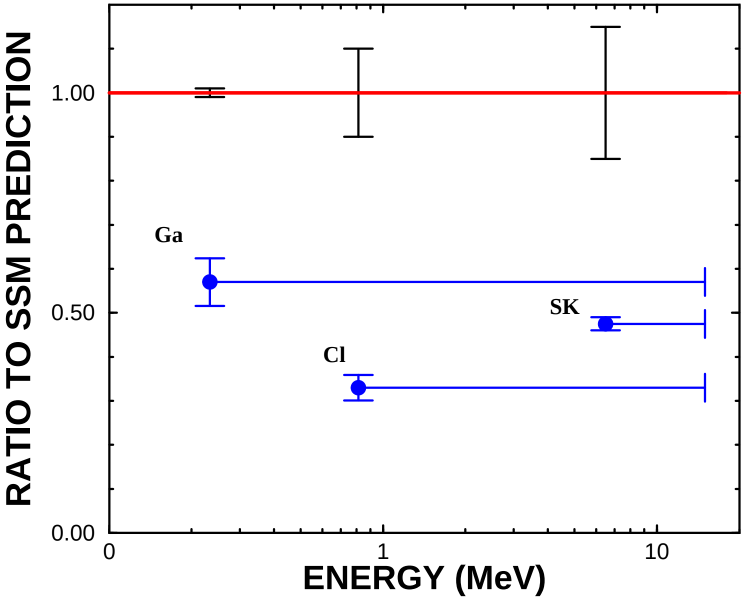




Solar Neutrino Flux Measurements

Two Classes of Experiment (pre-SNO)

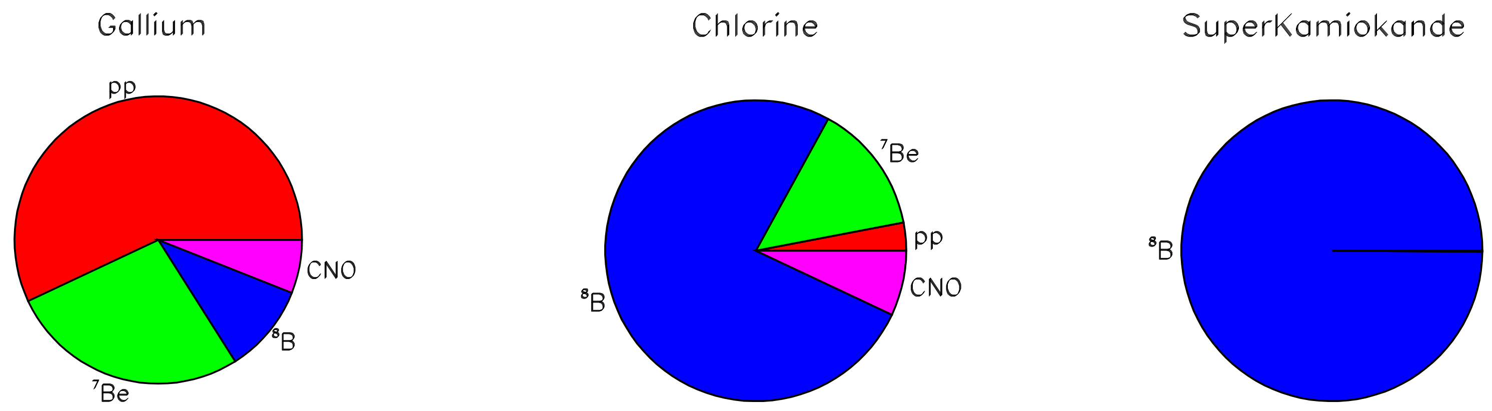
- Radiochemical
  - ν_e interactions convert target nuclei
  - Radioactive products extracted and counted after exposure time
- Water Cerenkov
  - Real-time detection of scattered atomic e^-'s
  - Mixed CC and NC sensitivity



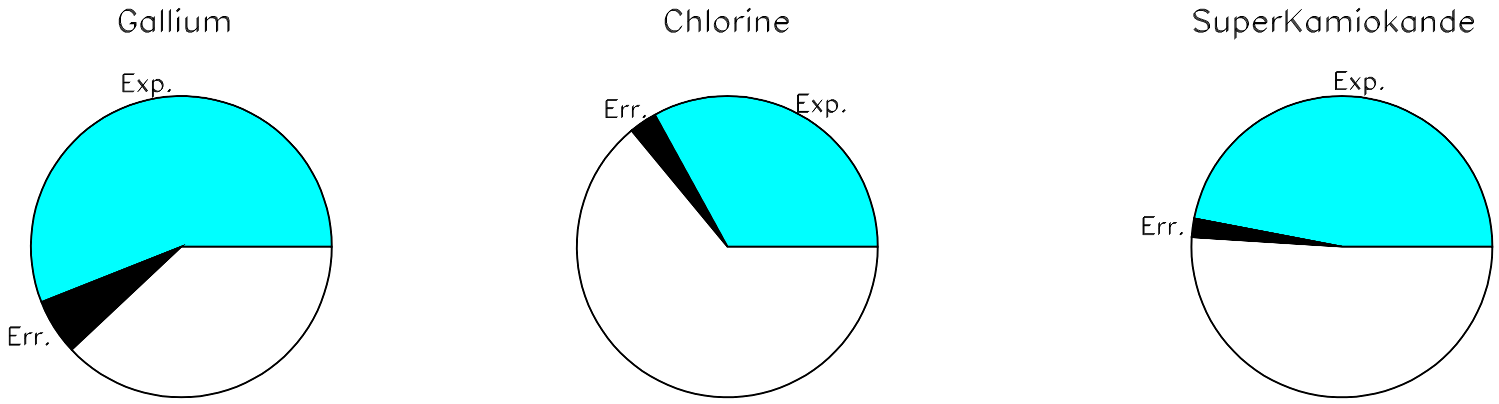
Experiment	Detection Reaction	Threshold	Primary Sources
Homestake	$\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}$	0.8 MeV	${}^7\text{Be}, {}^8\text{B}$
Kamiokande	$\nu_{e,(\mu,\tau)} + e \rightarrow \nu_{e,(\mu,\tau)} + e$	7.3 MeV	${}^8\text{B}$
SAGE, GALLEX/GNO	$\nu_e + {}^{71}\text{Ga} \rightarrow e^+ + {}^{71}\text{Ge}$	0.23 MeV	$pp, {}^7\text{Be}, {}^8\text{B}$
Super-K	$\nu_{e,(\mu,\tau)} + e \rightarrow \nu_{e,(\mu,\tau)} + e$	5 MeV	${}^8\text{B}$

The Solar Neutrino Problem

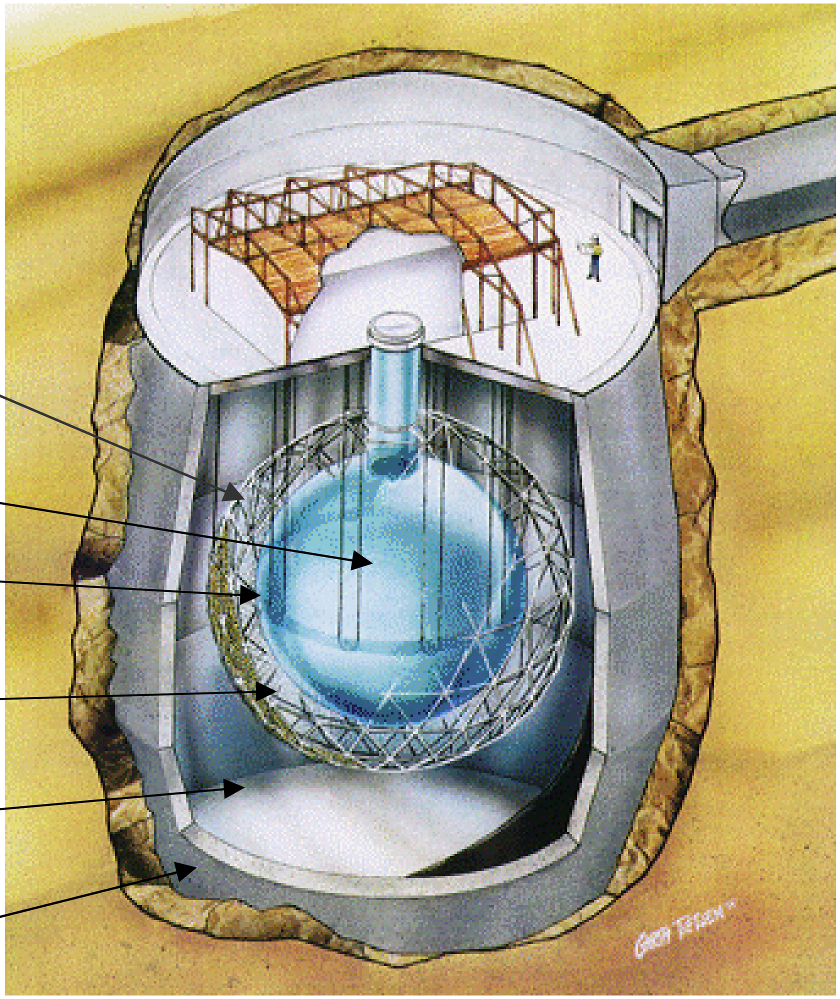
- Standard Solar Model Predictions:



- Measurements:



Sudbury Neutrino Observatory



2092 m to Surface

18 m Diameter Support Structure for 9500 PMTs, 60% coverage

1000 Tonnes D_2O

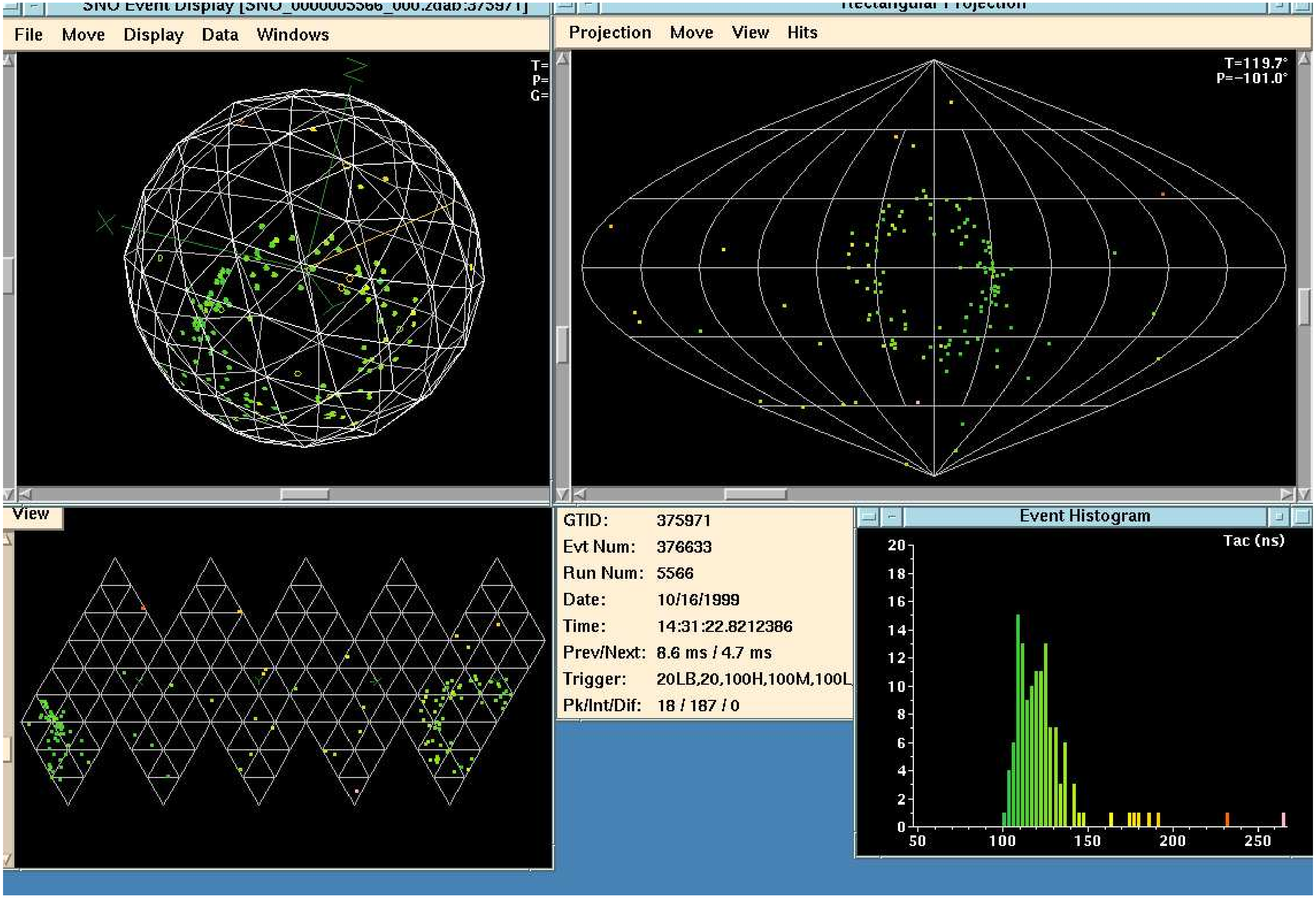
12 m Diameter Acrylic Vessel

1700 Tonnes Inner Shielding H_2O

5300 Tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

SNO Neutrino Event



GTID: 375971
Evt Num: 376633
Run Num: 5566
Date: 10/16/1999
Time: 14:31:22.8212386
Prev/Next: 8.6 ms / 4.7 ms
Trigger: 20LB,20,100H,100M,100L
Pk/Int/Dif: 18 / 187 / 0

Solar ν Interactions in SNO

SNO measures primarily ^{8}B neutrinos by three interactions:

Charged Current:

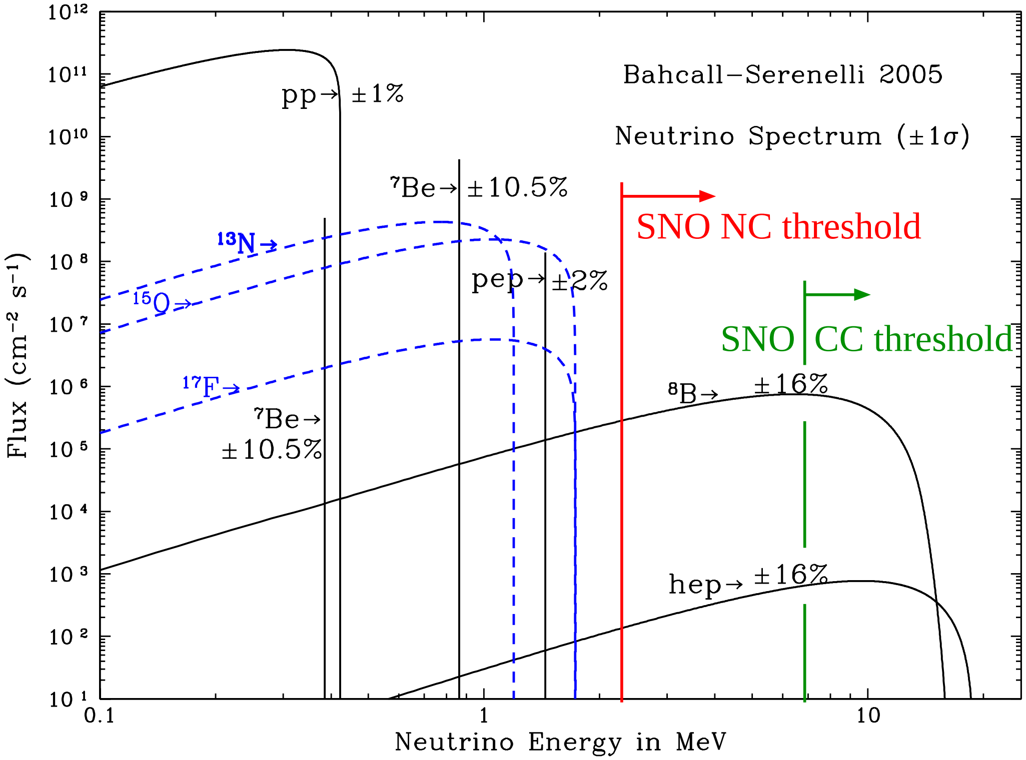
$$\nu_e + d \rightarrow p + p + e^-$$

Neutral Current:

$$\nu_x + d \rightarrow p + n + \nu_x$$

Elastic Scattering:

$$\nu_x + e \rightarrow \nu_x + e^-$$



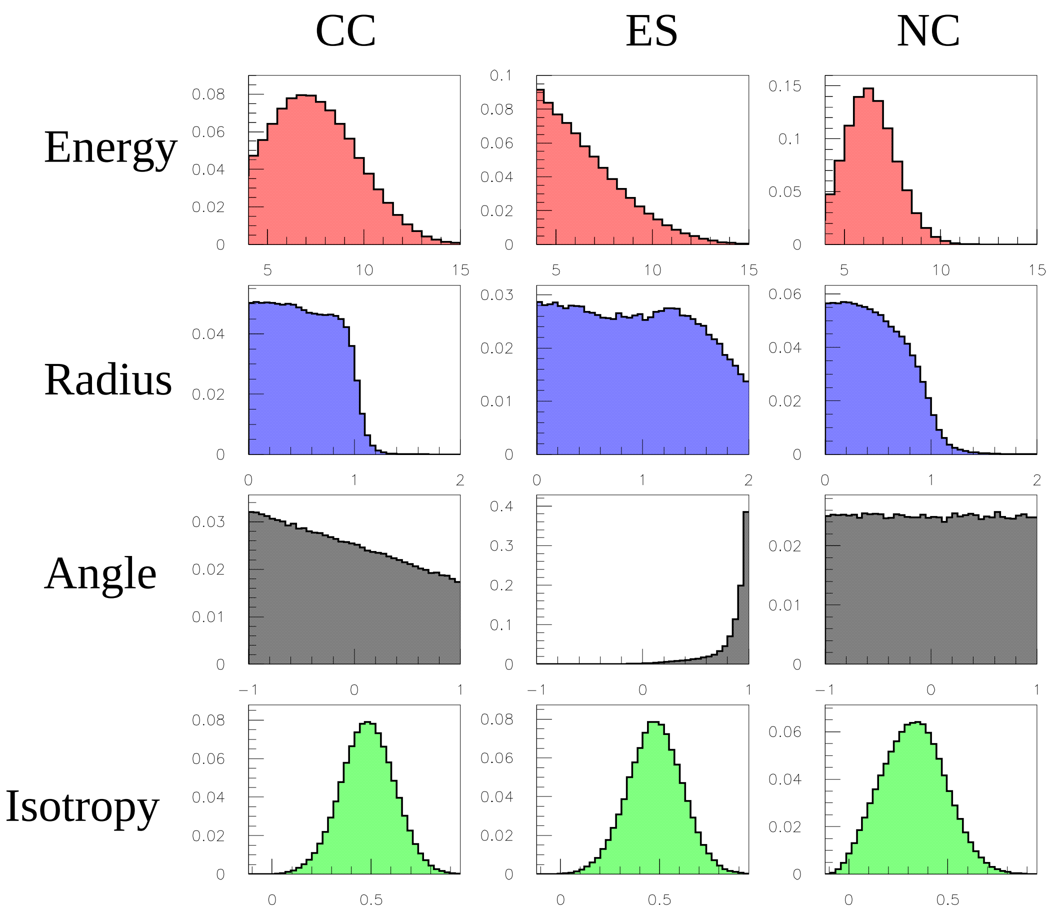
For the favored Large Mixing Angle (LMA) solution to solar neutrino problem:

$$|U_{e2}|^2 \approx \sin^2\theta_{12} \approx \frac{\phi_{CC}}{\phi_{NC}}$$

Three Phases of the SNO Experiment

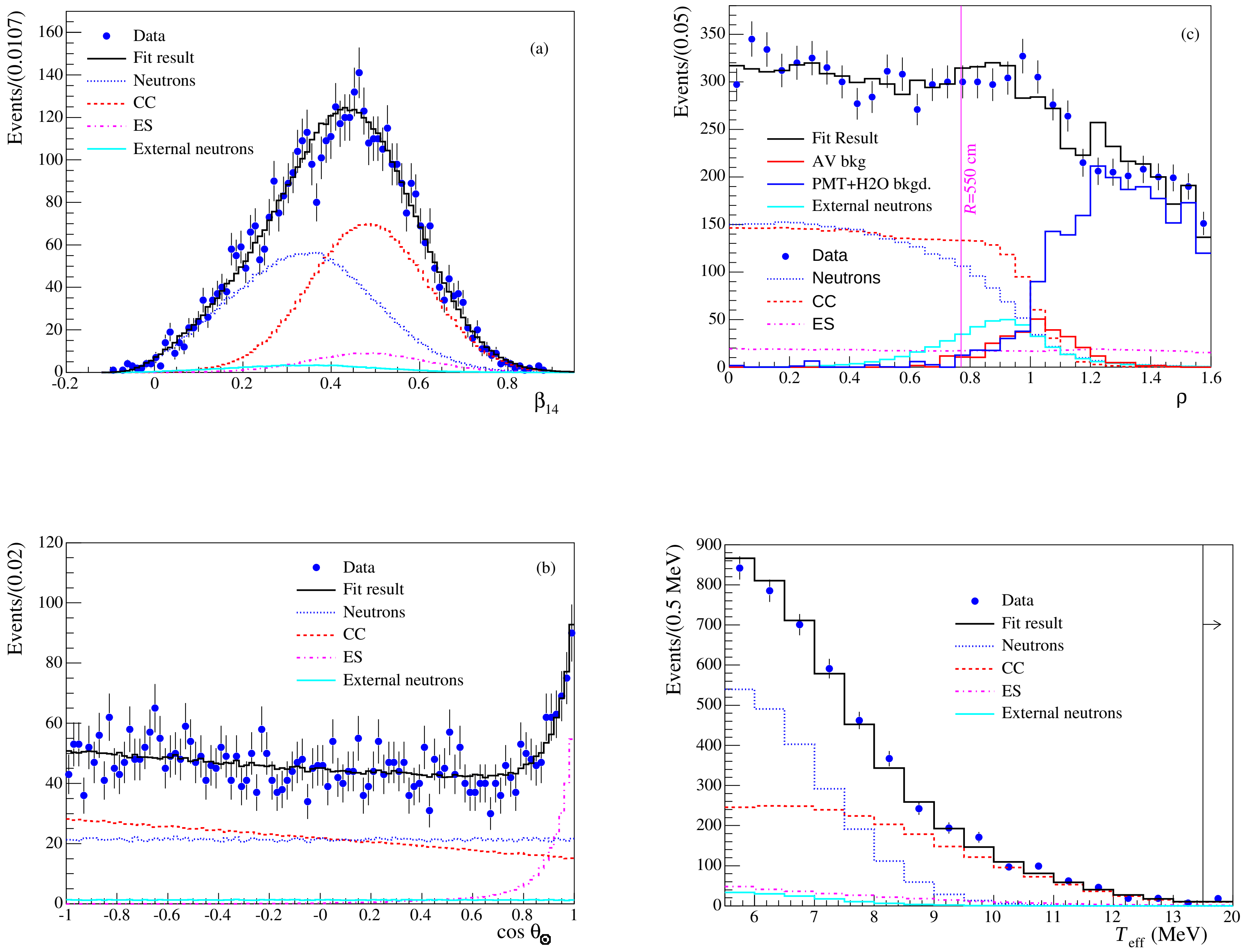
D$_2$O Phase	Salt Phase	NCD Phase
(pure D$_2$0)	(D$_2$O + 0.2% NaCl)	(^{3}He counters)
Nov 1999 - May 2001	July 2001 - Sept 2003	Dec 2004 - Dec 2006
$n + d \to t + \gamma$	$n + {}^{35}\text{Cl} \to {}^{36}\text{Cl} + \gamma$'s	$n + {}^{3}\text{He} \to p + t$
$(\sigma = 0.0005\,b)$	$(\sigma = 44\,b)$	$(\sigma = 5330\,b)$
Detect a Compton-scattered electron from a 6.25 MeV γ	Detect Compton-scattered electrons from multiple γ's totalling 8.6 MeV	Detect 764 keV of ionization from the charged particles in ^{3}He proportional counters
PRL 87, 071301 (2001)	PRL 92, 181301 (2004)	*Analysis in progress*
PRL 89, 011301 (2002)	PRL 92, 102004 (2004)	
PRL 89, 011302 (2002)	PRC 72, 055502 (2005)	
PRD 70, 093014 (2004)	PRD 72, 052010 (2005)	

SNO Signal Probability Distributions

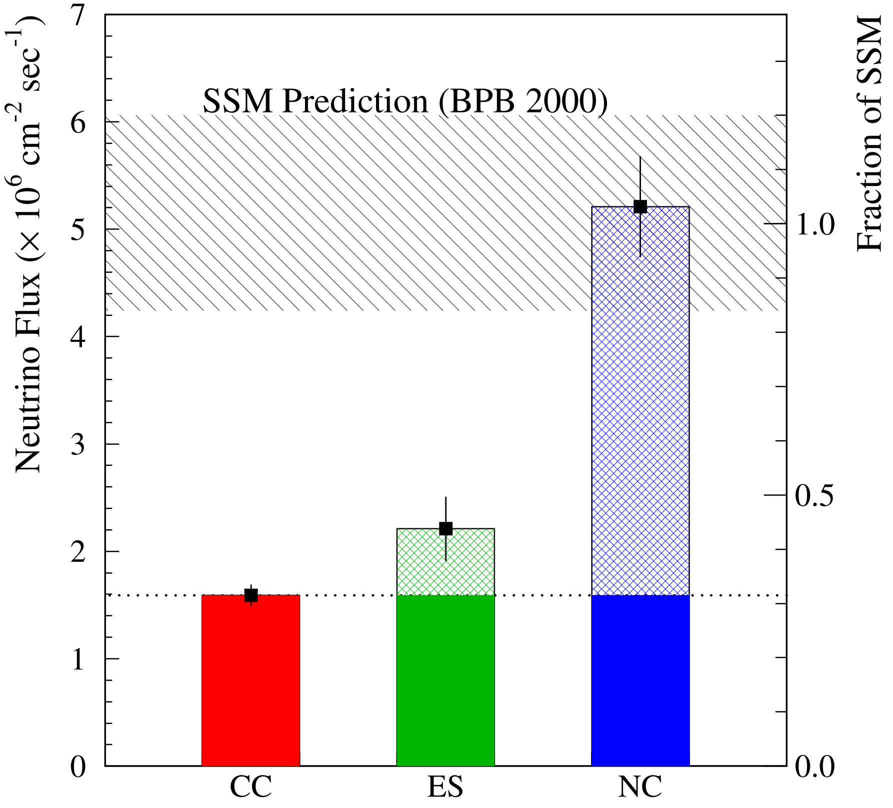


Fit the PDFs to the data to determine fluxes. Leave out the energy PDFs to fit for the spectral shapes.

Fits to SNO Salt Phase Data

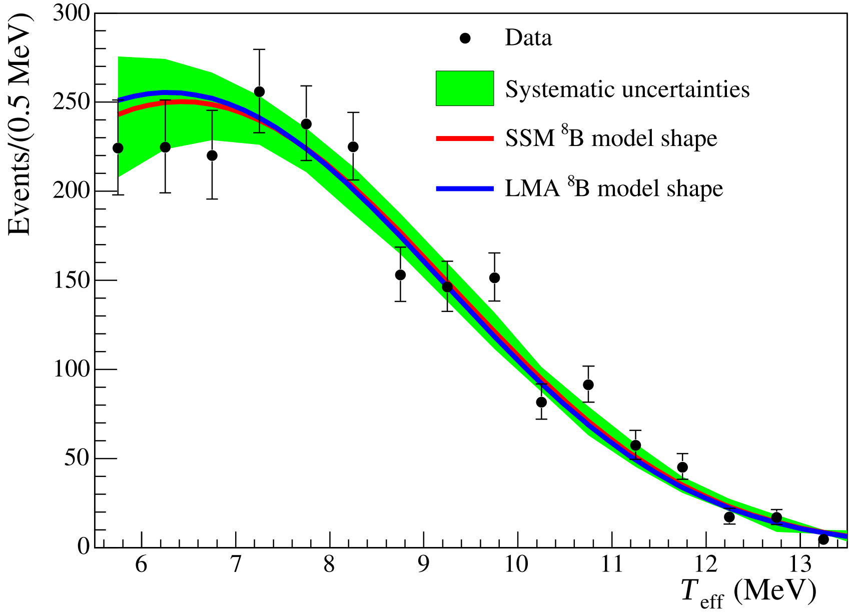


Evidence for Solar Neutrino Flavour Transformation



SNO: Direct evidence that

$$\phi(\nu_e) < \phi(\nu_{tot})$$

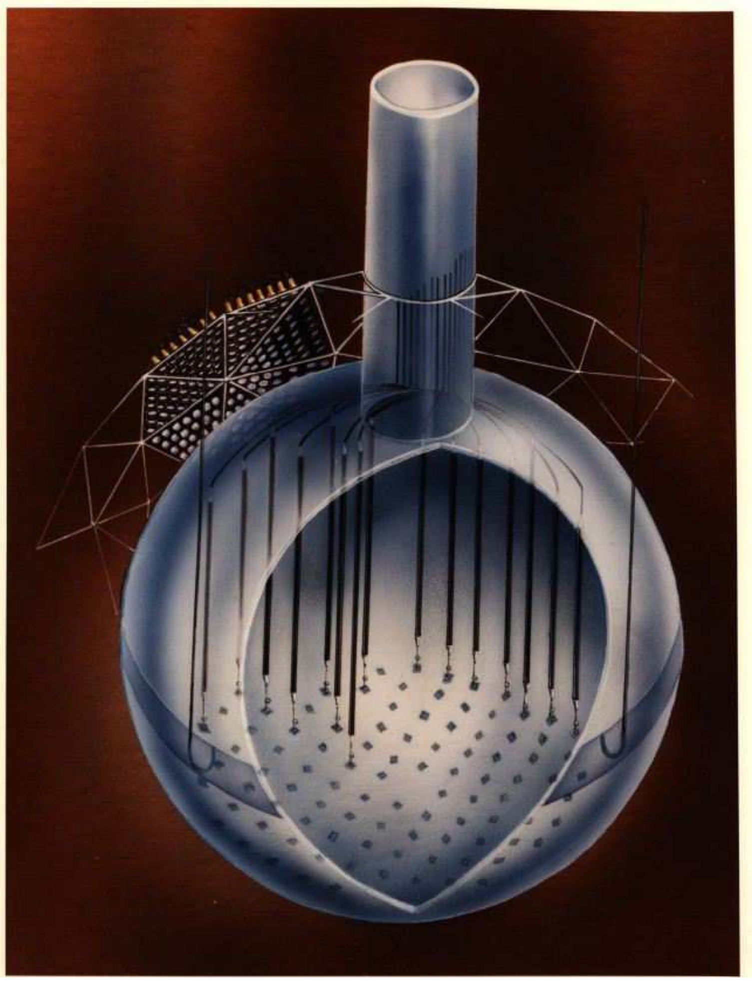


No evidence of spectral distortion.

$A_{DN} = 0.037 \pm 0.040$—no sign of matter effect.

Flavour transformation explains all solar neutrino results—but is it due to oscillation?

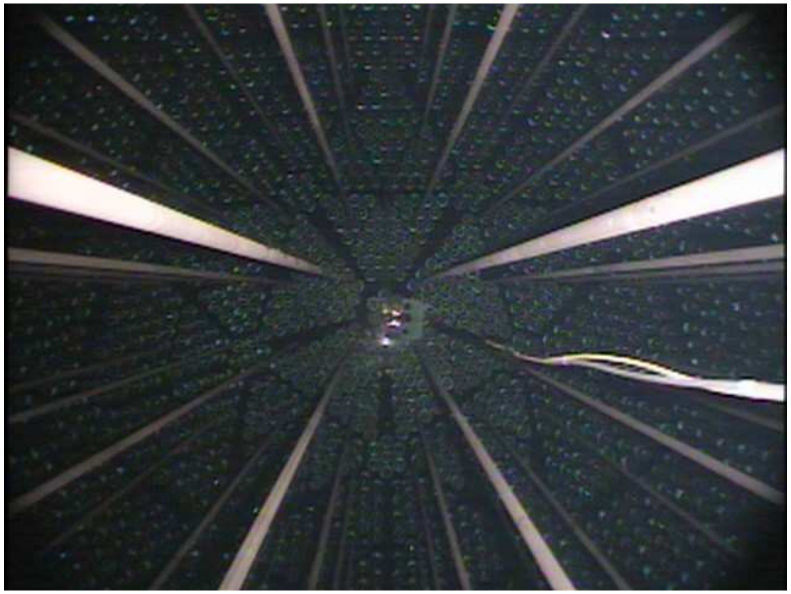
SNO Neutron Capture Detectors



An array of ^{3}He proportional counters inside D_2O to detect neutrons using the ionization signal from

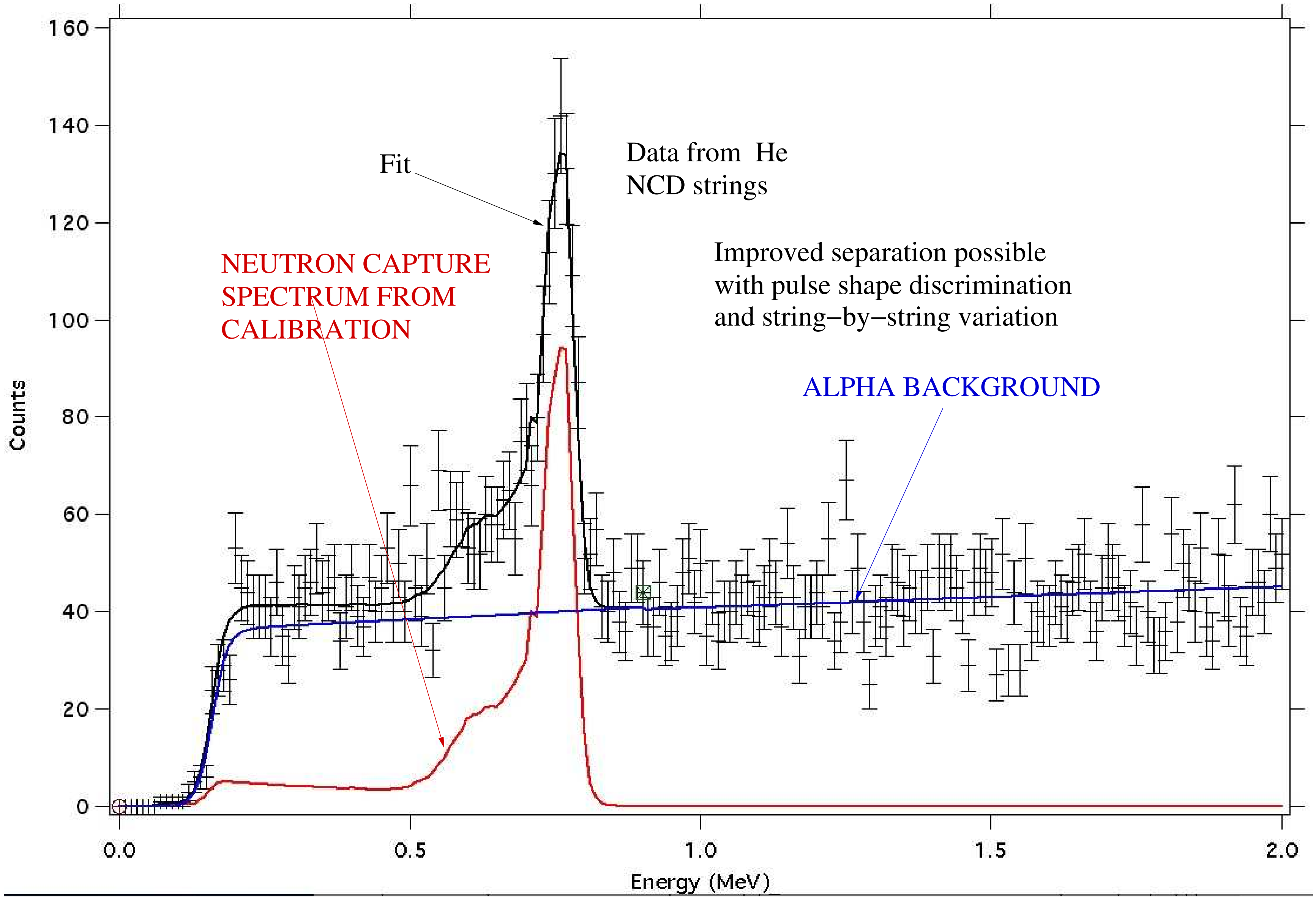
$$^3\text{He} + n \longrightarrow p + t$$

Photo of NCD counters from above



Goals of NCD phase:

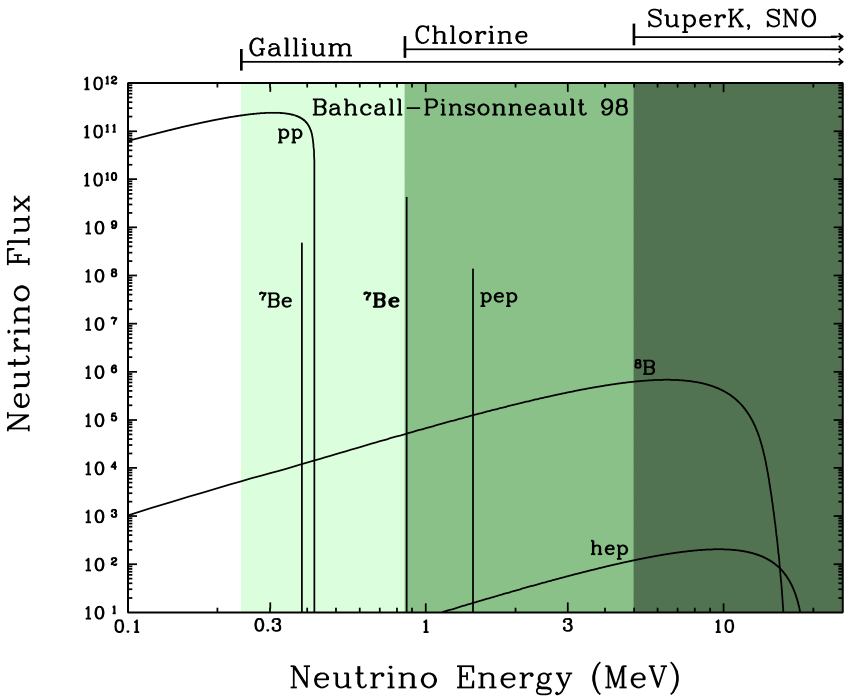
- Measure NC flux with different systematics
- Break CC/NC statistical correlation
- Reduced uncertainty on CC/NC ratio $\longrightarrow$ better measurement of θ_{12}

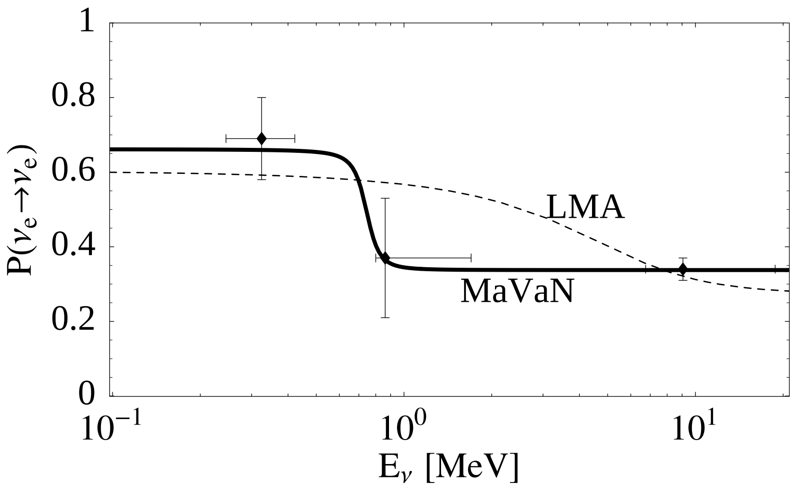


Data from He NCD strings

Improved separation possible with pulse shape discrimination and string–by–string variation

Future Solar Neutrino Experiments





Barger *et al*, hep-ph/0502196

There are various ideas for precision measurement of ^{7}Be and pep neutrinos by low-background scintillator detectors:

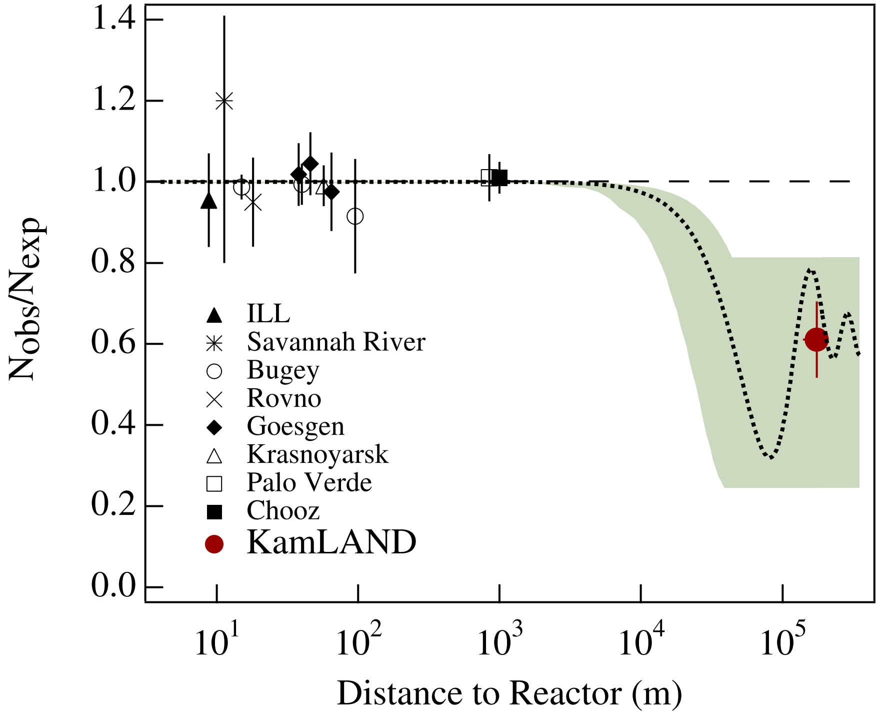
- Borexino
- KamLAND
- SNO+
- liquid noble gas detectors

Possible Motivations:

- Observe turn-up in LMA survival probability
- Constrain solar models
- Test exotic scenarios: non-standard interactions, mass-varying neutrinos, spin-flavour precession ...

See Tony Noble's talk for more.

Evidence for Reactor Neutrino Oscillations

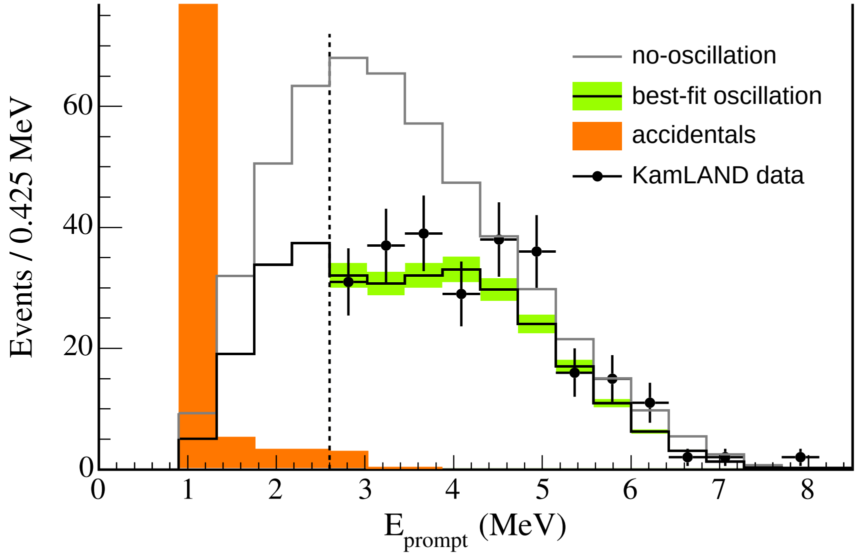


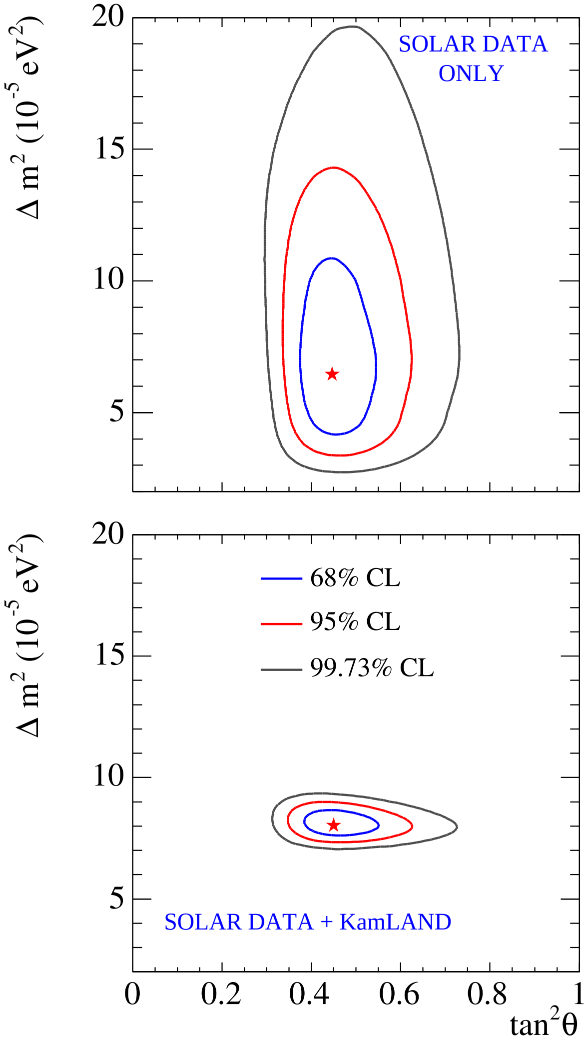
KamLAND: Observation of reactor neutrino disappearance at L/E value where solar neutrino effect occurs.

Evidence for Reactor Neutrino Oscillations

(PRL 94, 081801, 2005)

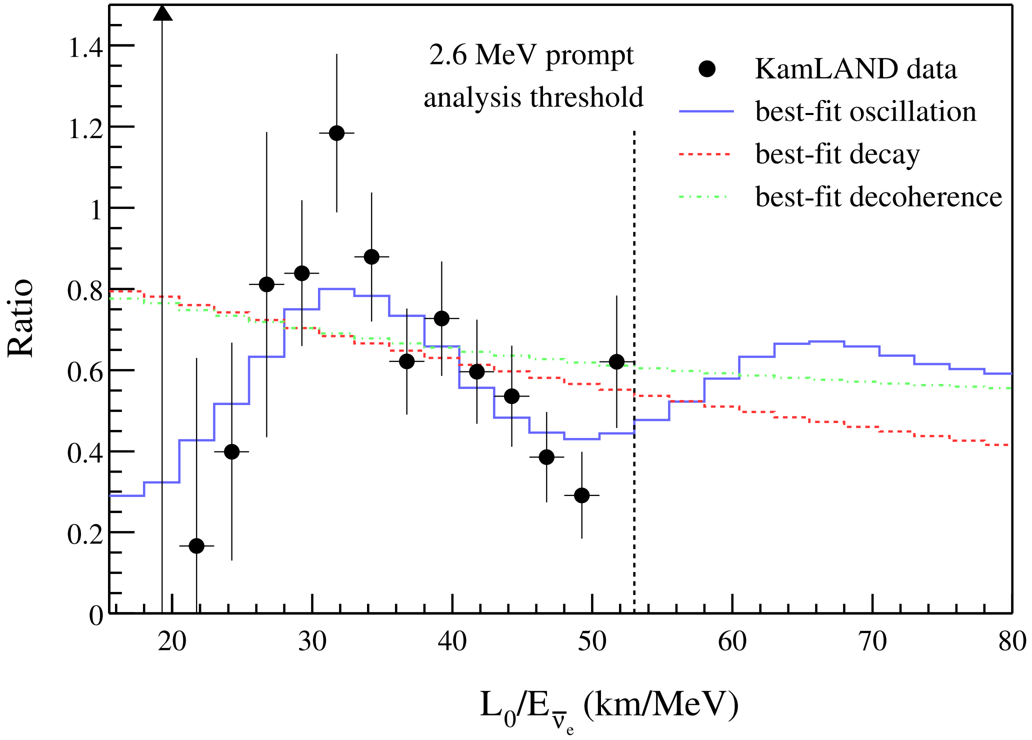
Spectral distortion seen in
reactor neutrino energy spectrum





Solar data constrains θ_{12}, while reactor data constrains Δm^2—extreme complementarity!

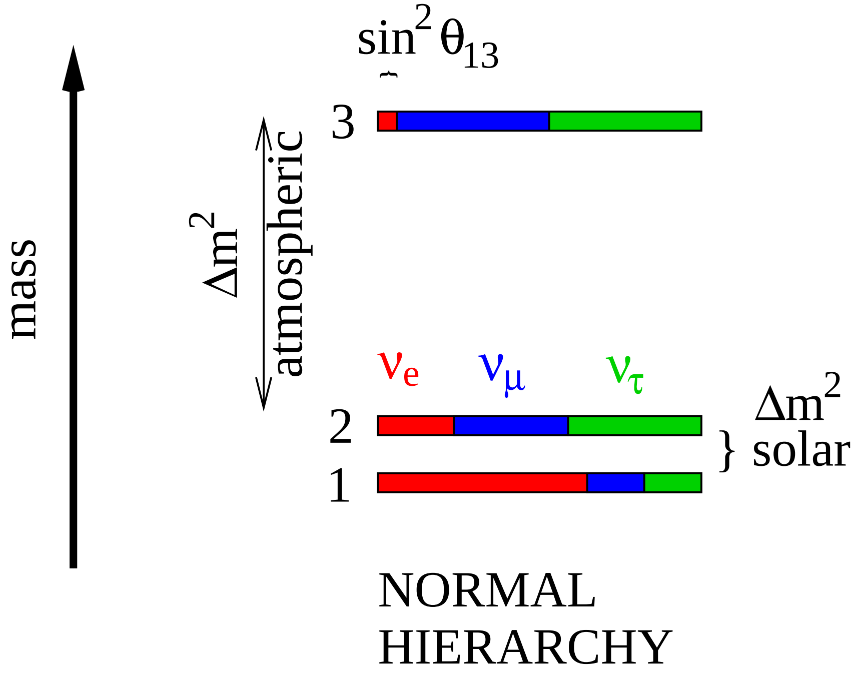
KamLAND: L/E analysis



KamLAND & solar neutrino together:

- confirm oscillation as the cause of the observed flavour transformation
- provide precise measurements of solar ν mixing parameters (e.g. $\delta(\Delta m^2) \sim 10\%$

The 3×3 framework



$$\Delta m^2_{12} \approx 8 \times 10^{-5}\ \text{eV}^2$$
$$|\Delta m^2_{23}| \approx 2.5 \times 10^{-3}\ \text{eV}^2$$

Two Δm^2 values, but hierarchy (sign of Δm^2_{23}) uncertain.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

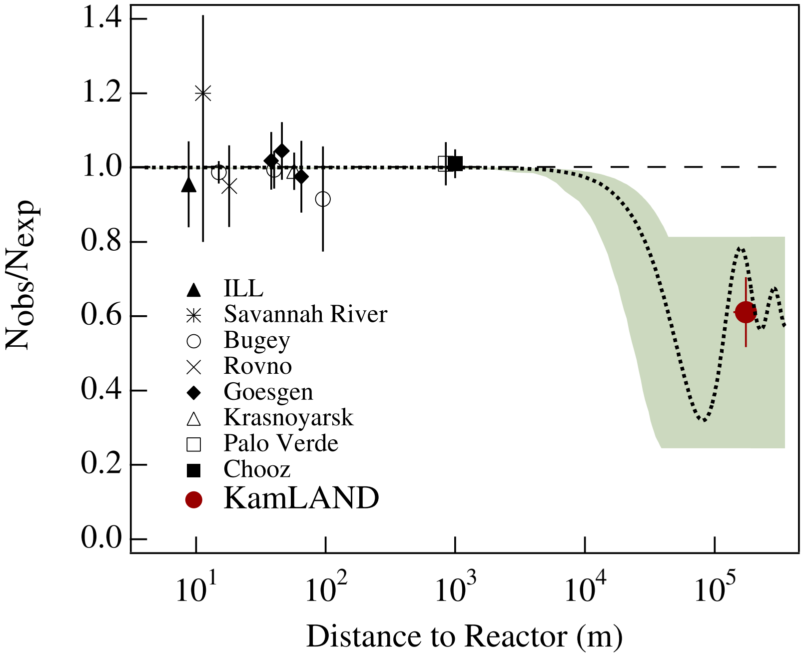
$$\approx \begin{bmatrix} 0.9 & 0.5 & s_{13}e^{i\delta} \\ -0.35 & 0.6 & 0.7 \\ 0.35 & -0.6 & 0.7 \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Two well-determined mixing parameters, but θ_{13} and δ_{CP} unknown!

Reactor θ_{13} Experiments

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{13} L}{E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m^2_{12} L}{E}\right)$$

Remember that KamLAND saw oscillation of reactor neutrinos at $L \approx 180$ km?



But what about those reactor experiments at *short* distances that saw nothing?

For $\Delta m^2_{13} \approx 2.5 \times 10^{-3}$ and $E \sim 5$ MeV, should have oscillation maximum at $L \approx 2$ km.

Since this is driven by oscillation between ν_1 and ν_3, the relevant mixing angle is the mixing between ν_e and ν_3—that is, θ_{13}.

CHOOZ limits:

$$R = 1.01 \pm 0.028\,(\text{stat}) \pm 0.027\,(\text{sys})$$

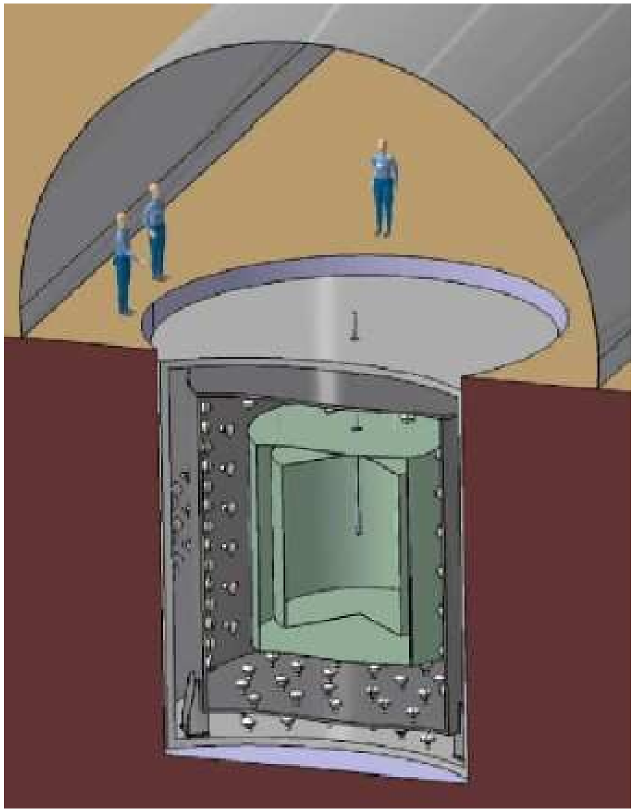
$$\sin^2 2\theta_{13} < 0.15\ (90\% C.L.)$$

New θ_{13} Experiments

A next generation reactor experiment could improve the θ_{13} limit by an order of magnitude by:

- Large increase in statistics: use a GW-scale reactor and run for a few hundred GW-tonne-years
- Reduce systematics to $< 1\%$: use both a near and a far detector to cancel systematics.
- Better detector design

Reactor experiments sensitive *only* to θ_{13}, not δ_{CP} or matter effects. Very complementary!



The Double CHOOZ far detector

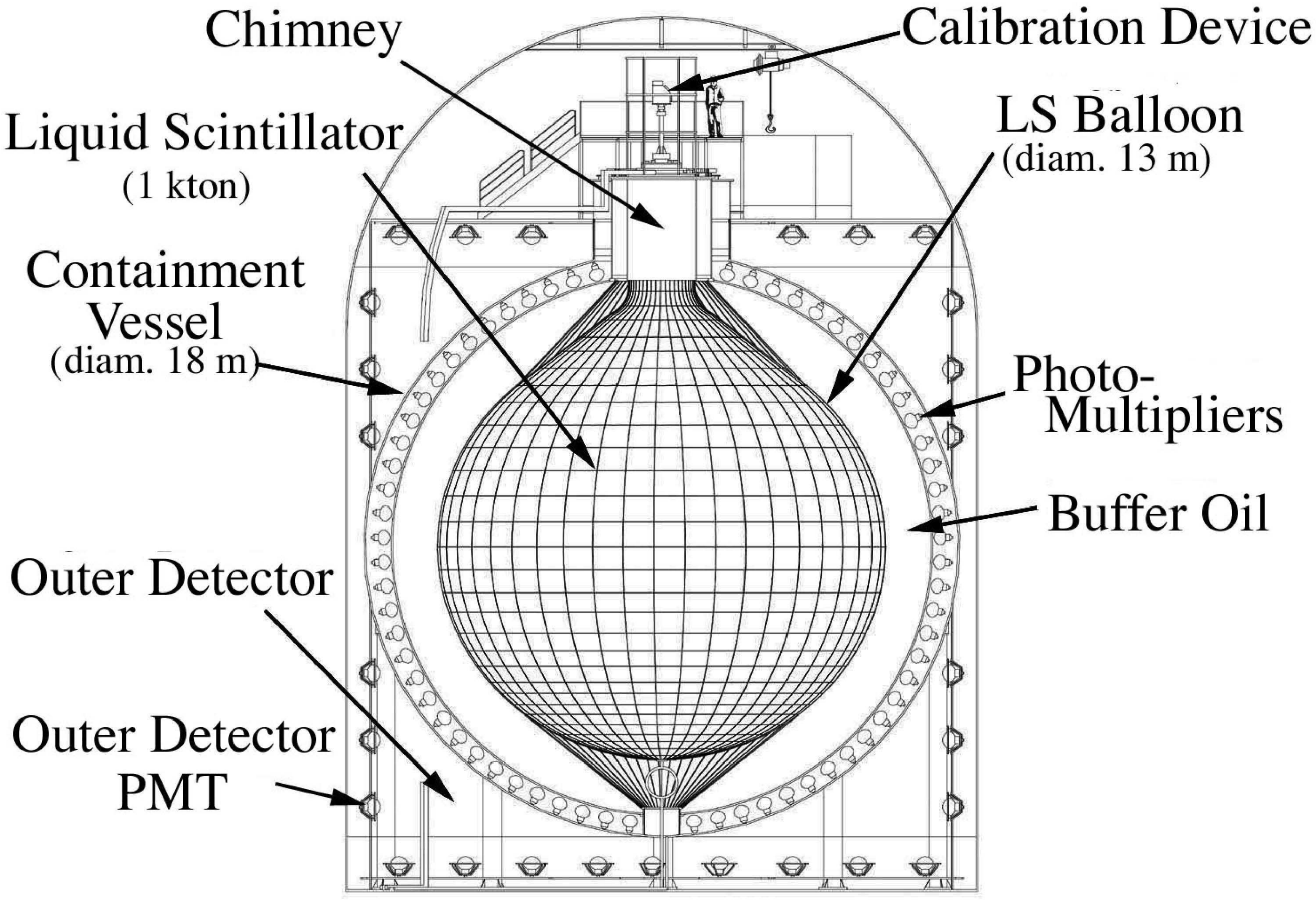
Many proposals: Double CHOOZ (France), Daya Bay (China), Angra (Brazil), RENO (Korea), ...

Conclusions

- Neutrinos have mass and oscillate. Compelling evidence from four different kinds of experiments:
    1. atmospheric neutrinos
    2. solar neutrinos
    3. reactor neutrinos
    4. long baseline neutrino beams (not covered in this talk)
- Neutrino mixing opens a whole new area of lepton flavour physics. *This is new physics beyond the Standard Model, involving new fields and new fundamental constants!*
- Non-accelerator neutrino physics has played the critical role in the revolution in neutrino physics.

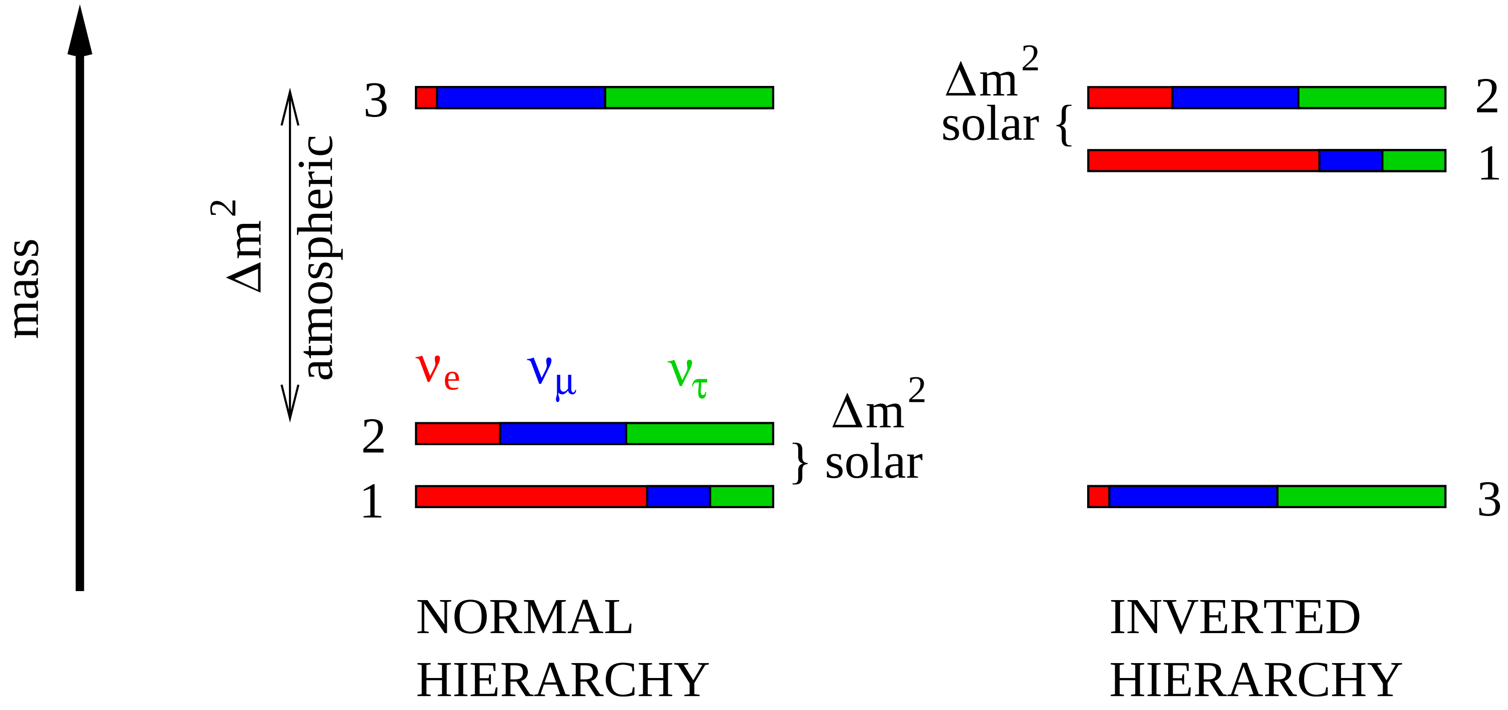
Backup slides follow

KamLAND detector



(hep-ex/0212021)

Neutrino Mass Hierarchy



$\Delta m^2_{atm} \approx 2.5 \times 10^{-3}$ eV^2 $\Delta m^2_{sol} \approx 8 \times 10^{-5}$ eV^2

Neutrino Mixing Matrix

Adjust L/E to view oscillations at different Δm^2's

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

Atmospheric ν's:	Short baseline reactor ν's:	Solar ν's:
$\theta_{23} \approx \pi/4$	$\theta_{13} < \pi/20$	$\theta_{12} \approx \pi/6$
Maximal mixing! (?)	Small, quark-like mixing	Large, non-maximal mixing

Compare to identical parameterization of CKM matrix ...

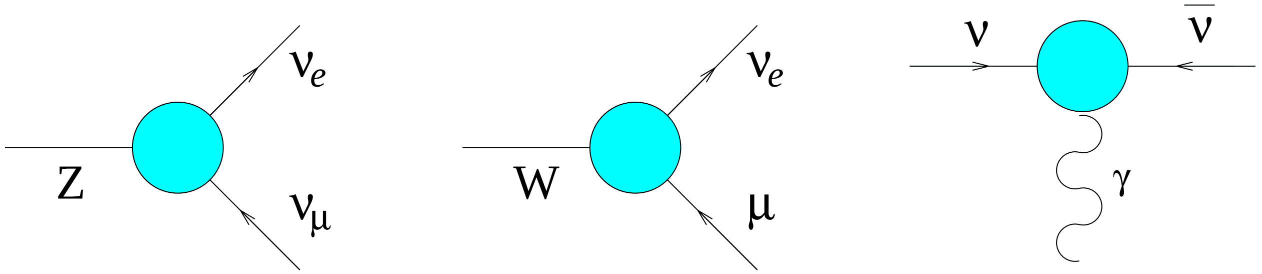
$\theta_{23} \approx \pi/76$	$\theta_{13} \approx \pi/870$	$\theta_{12} \approx \pi/14$

Non-Standard Neutrino Interactions

Neutrino oscillation adds mixing between mass and flavour eigenstates to the SM, but doesn't alter the allowed interactions themselves. All interactions are still left-handed, flavour-conserving, and obey flavour universality.

But many models (GUT or otherwise) allow for violations of all of these.

Interpretation of data in terms of neutrino oscillation generally ignores the possibility of these terms.

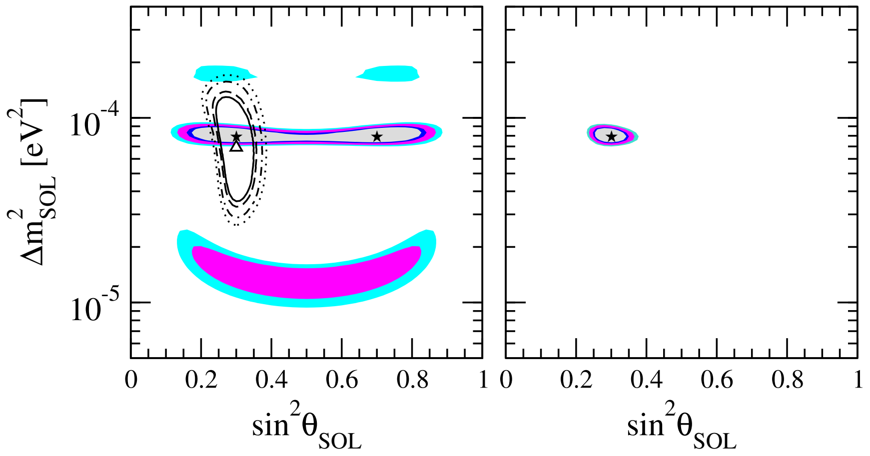


1. Flavour-changing neutral currents
2. Altered vertex factors
3. Large magnetic moments (“spin-flavour precession”)

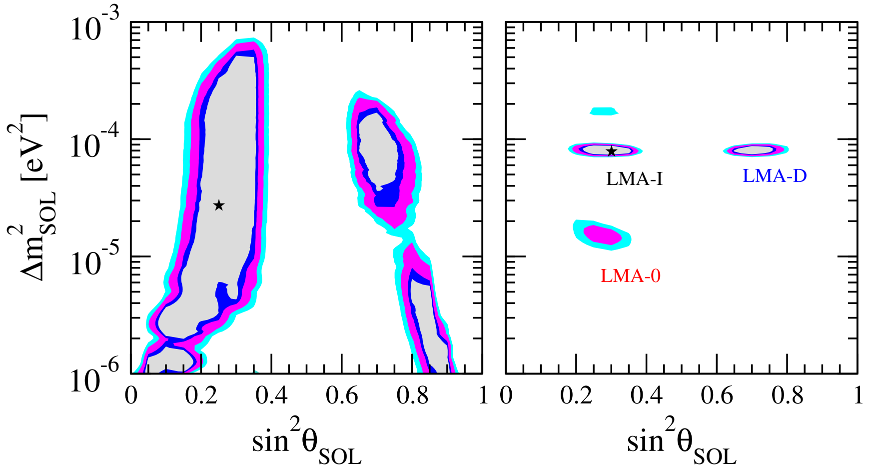
Can be present as linear terms in oscillation (appear as squared terms in decays)

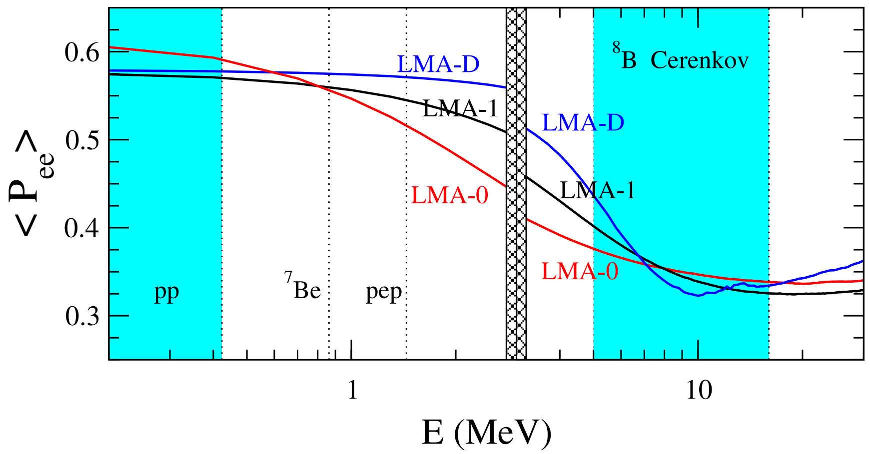
An example: non-standard neutrino interactions with solar ν's

Standard solar, reactor analysis



Solar, reactor analysis with NSI





Influence of NSI on effective solar neutrino oscillation probability

Plots from Mirana, Tortola, and Valle (hep-ph/0406280)

Bad news: neutrino interactions are the most poorly constrained of all SM interactions, for obvious experimental reasons

Good news: searches for NSI are sensitive to new physics at the TeV scale

Determining the Absolute Neutrino Mass

What is the Absolute Neutrino Mass?

Three extreme cases:

NORMAL HIERARCHICAL

$m_1 \ll m_2 \ll m_3$

$$\begin{aligned} m_1 &\approx 0 \\ m_2 &\approx \sqrt{\Delta m^2_{12}} \\ &\approx 0.009\,\mathrm{eV} \\ m_3 &\approx \sqrt{\Delta m^2_{23}} \\ &\approx 0.050\,\mathrm{eV} \end{aligned}$$

(Most like other fermions.

Favoured by GUTs)

INVERTED HIERARCHY

$m_1 \approx m_2 \gg m_3$

$$\begin{aligned} m_1 &\approx \sqrt{\Delta m^2_{23}} \\ &\approx 0.050\,\mathrm{eV} \\ m_2 &\approx \sqrt{\Delta m^2_{23}} \\ &\approx 0.050\,\mathrm{eV} \\ m_3 &\approx 0 \end{aligned}$$

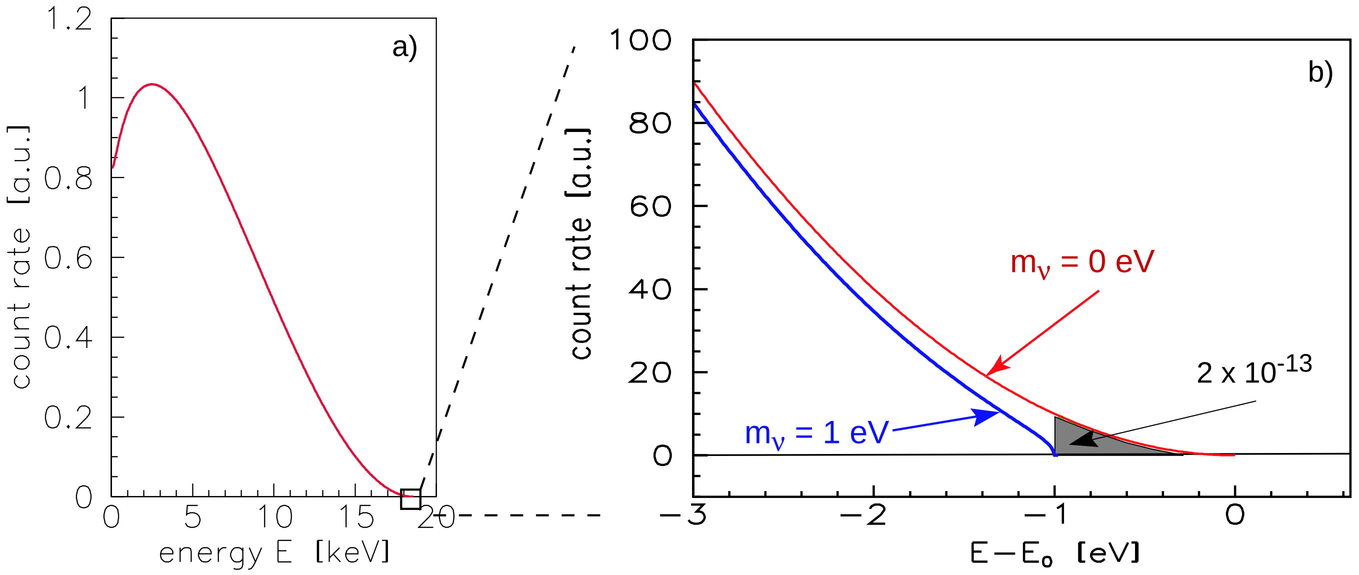
DEGENERATE

$m_1 \approx m_2 \approx m_3$

$$\begin{aligned} m_1 &\sim 0.2\,\mathrm{eV} \\ m_2 &\sim 0.2\,\mathrm{eV} \\ m_3 &\sim 0.2\,\mathrm{eV} \end{aligned}$$

Personal prejudice favors normal hierarchical, but all are possible, as are intermediate cases.

Direct Mass Limits



KATRIN collaboration, hep-ex/0109033

Most sensitive ν_e searches come from measuring the endpoint of the energy spectrum of tritium decay.

$$m(\nu_e) \leq 2.5\,\mathrm{eV}\ \ (95\%\ C.L.)$$

KATRIN proposal: new tritium endpoint measurement with sensitivity down to 0.2 eV

Collider limits:

$m(\nu_\mu) < 190$ keV (90% C.L.)

$m(\nu_\tau) < 18.2$ MeV (95% C.L.)

Cosmological Mass Limits

Neutrinos constitute “hot dark matter”:

$$\Omega_\nu h^2 = \frac{m_1 + m_2 + m_3}{94\,\mathrm{eV}}$$

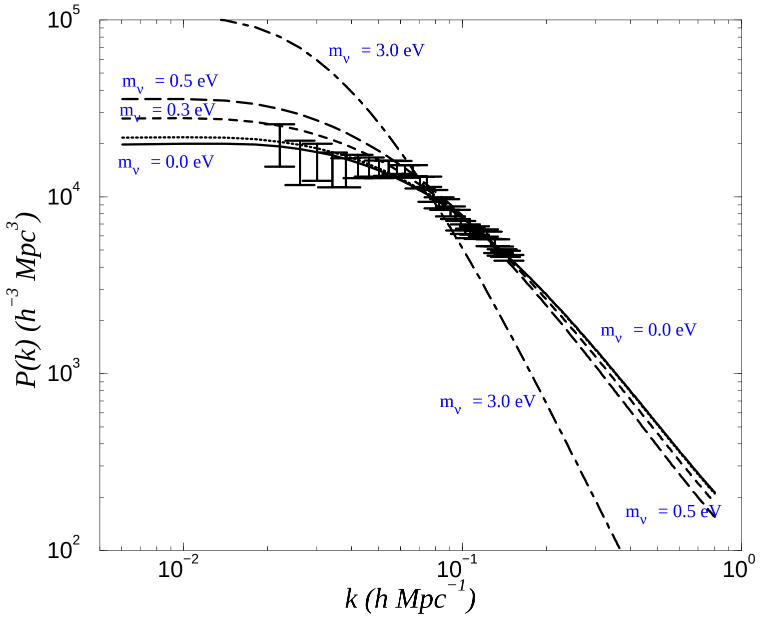
$$n_\nu \approx 112\,\mathrm{cm}^{-3}$$

Neutrinos reduce clustering at small angular scales during structure formation, since they “stream out of” small density perturbations.

This can leave signatures in, for example

- CMB
- large scale structure
- weak lenses

Oscillation experiments limit $\Omega_\nu > 0.001$, about the same mass as in stars!



Effects of neutrino mass on large scale structure (angular power spectrum), with

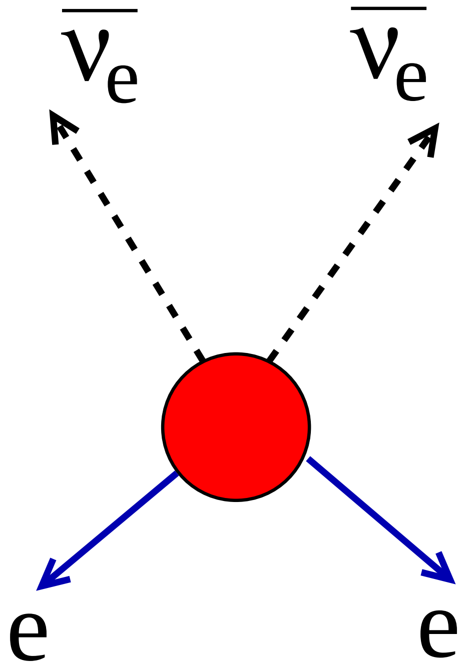
2dFGRS data superimposed. Adopted from Elgaroy and Lahav, hep-ph/0412075

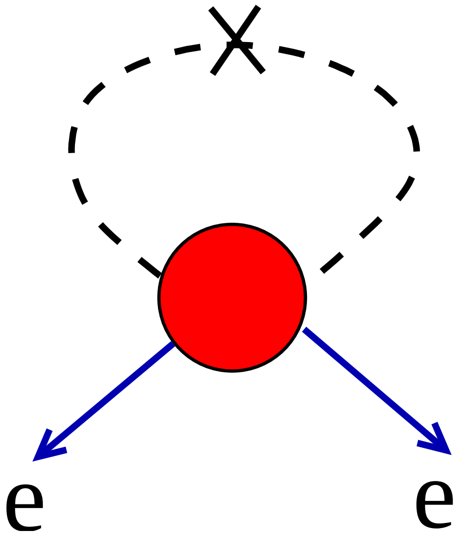
Various model-dependent limits:

$$\sum_i m_i <\sim 0.4 - 0.7\,\mathrm{eV}$$

Cosmology could well be the only way to determine m_ν if small!

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)





Ordinary double beta decay occurs when single beta decay is energetically surpressed, but double beta decay isn't.

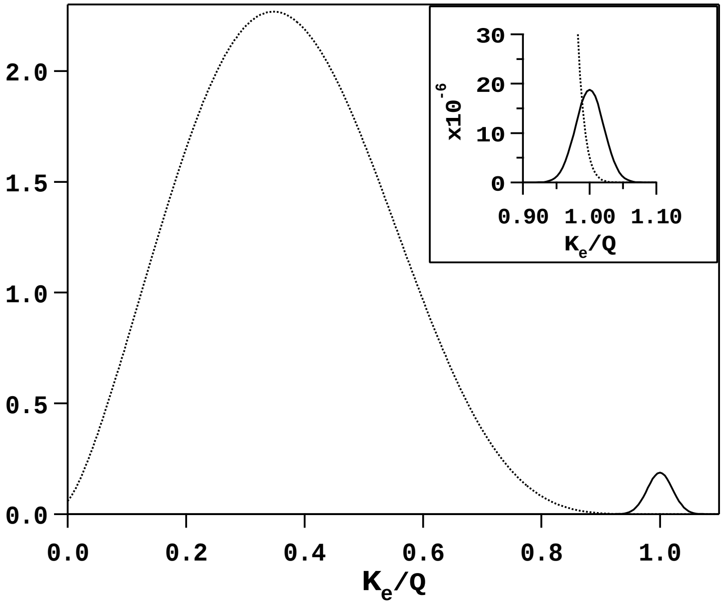
A doubly weak process—very rare!

Neutrinoless double beta decay violates lepton number ($|\Delta L| = 2$), but is allowed if a neutrino is its own antiparticle.

Rate of $0\nu\beta\beta$ decay depends on effective neutrino mass:

$$R \propto \langle m_\nu \rangle^2 = \left| \sum_i^N U_{ei}^2 m_i \right|^2$$

Double Beta Decay—Experimental Technique



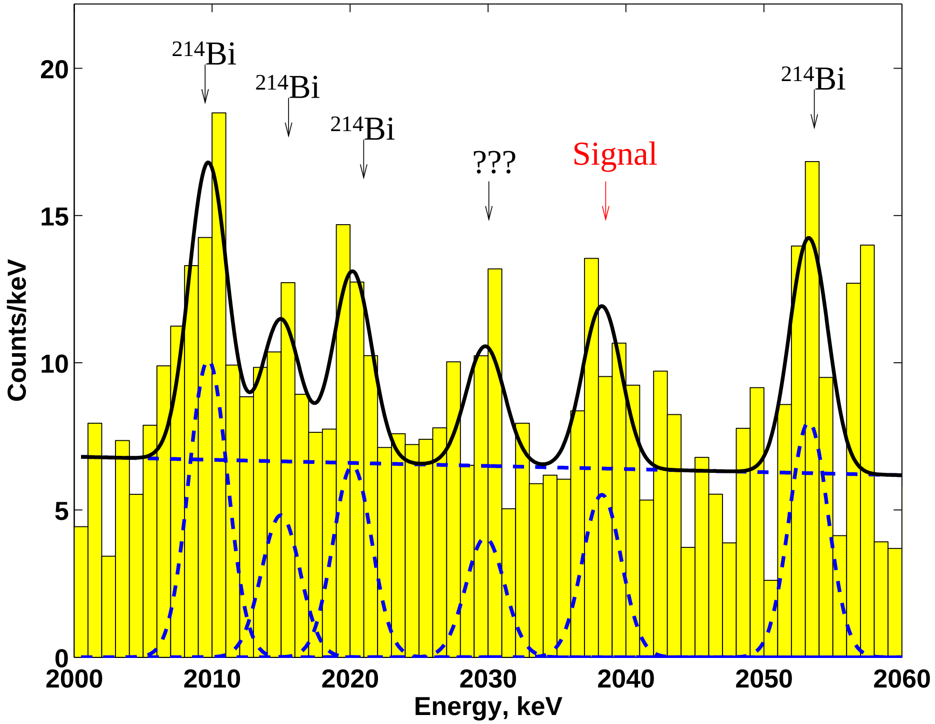
Experimental signature: the sum of the two electrons' energies yields a peak at the endpoint.

Current limits:

Isotope	$T^{0\nu}_{1/2}$ (y)	$\langle m_\nu \rangle$ (eV)
^{48}Ca	$> 9.5 \times 10^{21} (76\%)$	< 8.3
^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35
	$> 1.6 \times 10^{25}$	$< 0.33 - 1.35$
^{82}Se	$> 2.7 \times 10^{22} (68\%)$	< 5
^{100}Mo	$> 5.5 \times 10^{22}$	< 2.1
^{116}Cd	$> 7 \times 10^{22}$	< 2.6
^{128}Te	$> 7.7 \times 10^{24}$	$< 1.1 - 1.5$
^{130}Te	$> 1.4 \times 10^{23}$	$< 1.1 - 2.6$
^{136}Xe	$> 4.4 \times 10^{23}$	$< 1.8 - 5.2$
^{150}Nd	$> 1.2 \times 10^{21}$	< 3

(Elliott & Vogel, Ann. Rev. Nucl. Part. Sci 52 (2002))

Claimed Detection for Moscow-Heidelberg Experiment



Adapted from H.V. Klapdor-Kleingrothaus, hep-ph/0512263

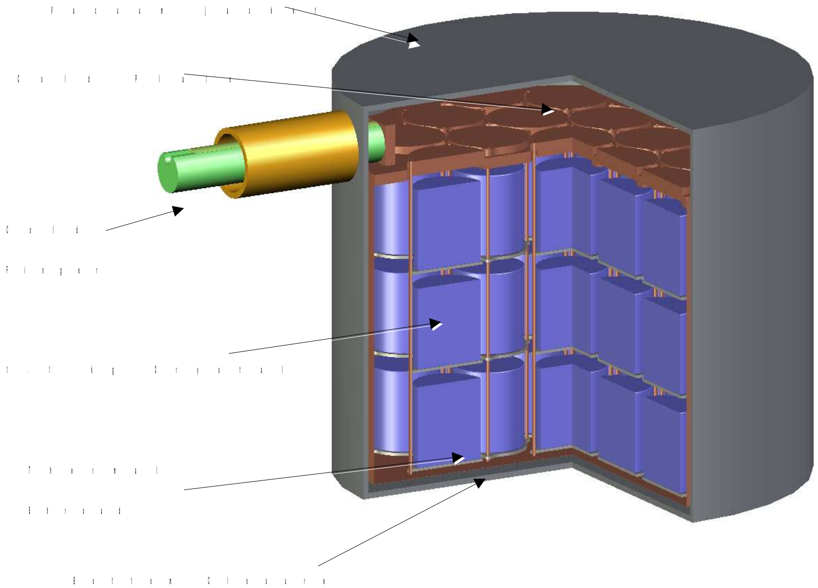
The Moscow-Heidelberg collaboration has previously published an upper limit on $0\nu\beta\beta$ decay in ^{76}Ge.

In recent years a small subset of the Moscow-Heidelberg collaboration claimed to see evidence for a positive signal (4.2σ).

Inferred effective mass is $m_\nu \approx 0.2 - 0.6$ eV

Claim is “controversial”

The MAJORANA Experiment

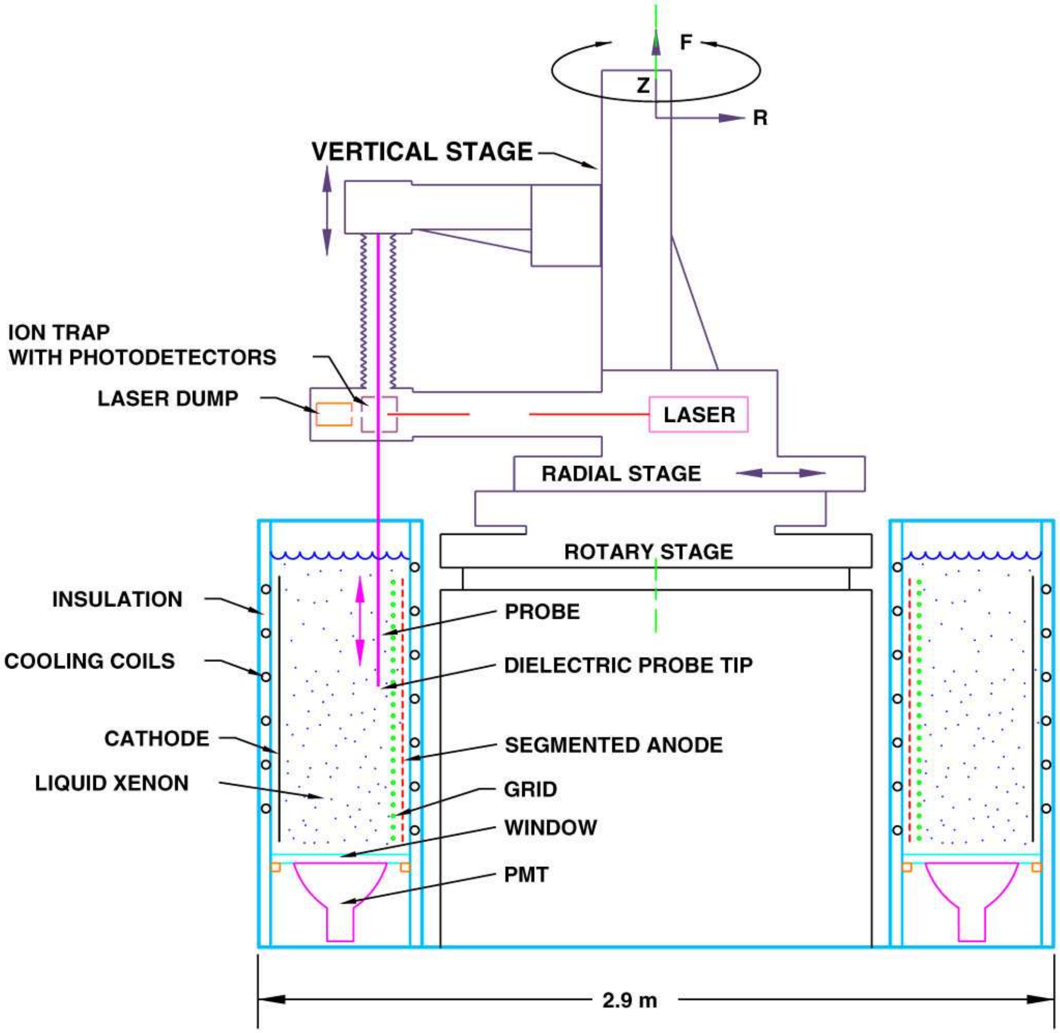


Proposal for a massive germanium experiment

- 86% enriched ^{76}Ge
- Ge gives extremely good energy resolution—great for resolving endpoint peak
- Goal is 2500 kg-years exposure
- Very clean materials, pulse shape discrimination, and segmented detectors to reject backgrounds
- “Proven” technology

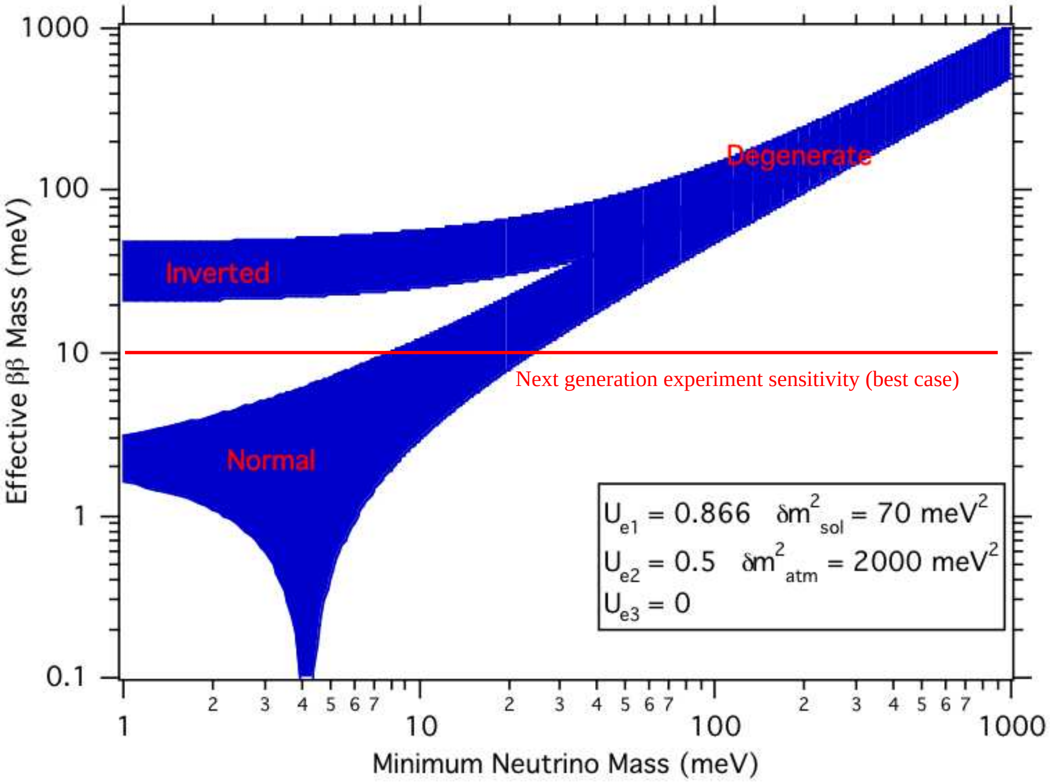
Sensitivity goal: < 50 meV

The EXO Experiment



Look at 10 tonnes of ^{136}Xe in a liquid or gas TPC. Use laser spectroscopy on the resulting ion to confirm it is barium, rejecting backgrounds. Sensitivity of ~ 10 meV

Double Beta Decay Sensitivity



Proposed double beta decay experiments, if successfully, could distinguish between normal and inverted hierarchy, but only if ν's are Majorana particles.

Null result by itself cannot rule out either Majorana neutrinos or largish masses.

No real idea how to improve sensitivity to cover normal hierarchy.