Experimental Evidence for Neutrino Mass

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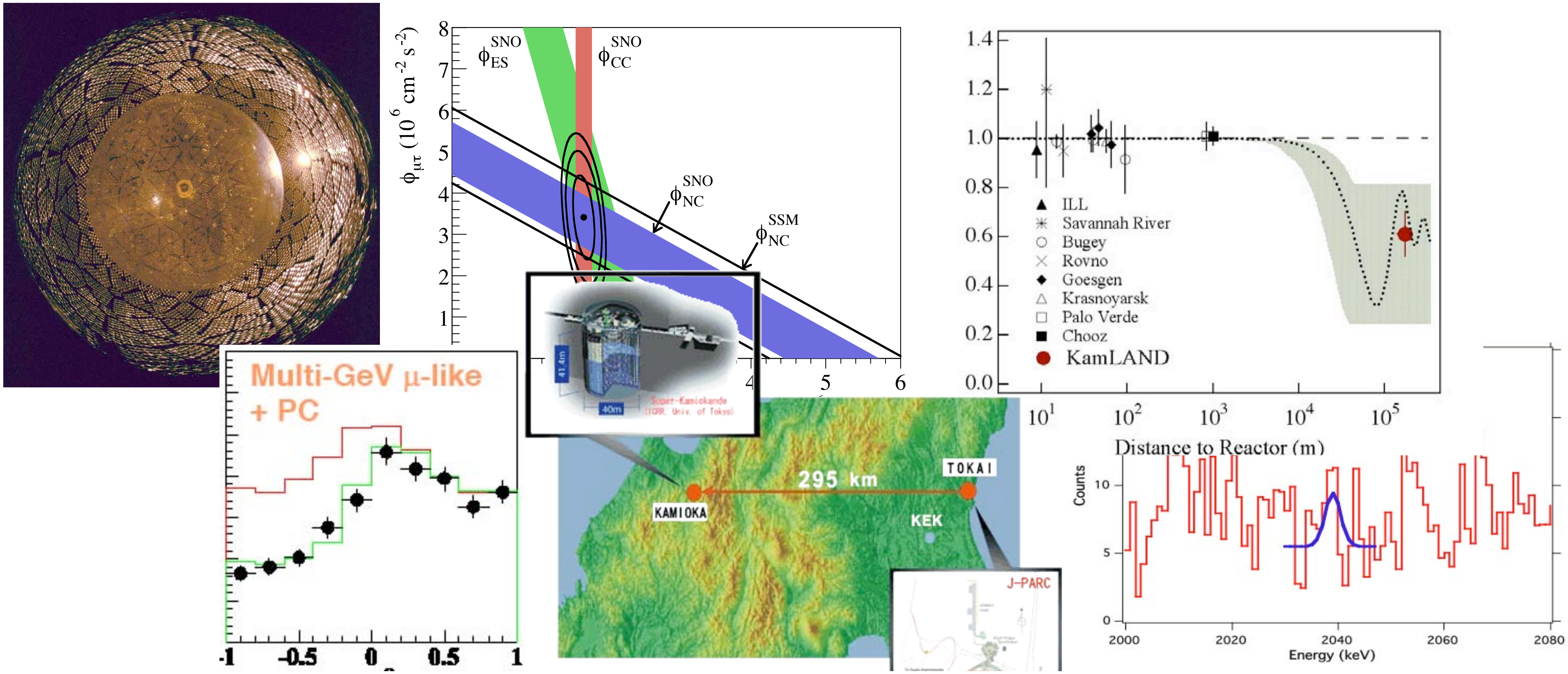


“Standard Model” Neutrino Physics

1914	Electron Spectrum in β decay is continuous
1930	Pauli postulates that a new particle is emitted
1933	Fermi names the new particle neutrino and introduces four-fermion interaction
1956	Reines and Cowan discover the neutrino
1962	At least two neutrinos: $\nu_e \neq \nu_\mu$
1989	Measurement of Z width at CERN → $N_\nu=3$
2002	tau neutrino discovered.

Neutrino Astrophysics

1938 Bethe & Critchfield

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

1946 Pontecorvo, 1949 Alvarez

propose neutrino detection through

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

1960’s Ray Davis builds chlorine detector

John Bahcall, generates SSM & solar n flux predictions

“…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars...”

First Indication of ‘Non-Standard’ Neutrinos

Solar Neutrino Flux Measurements

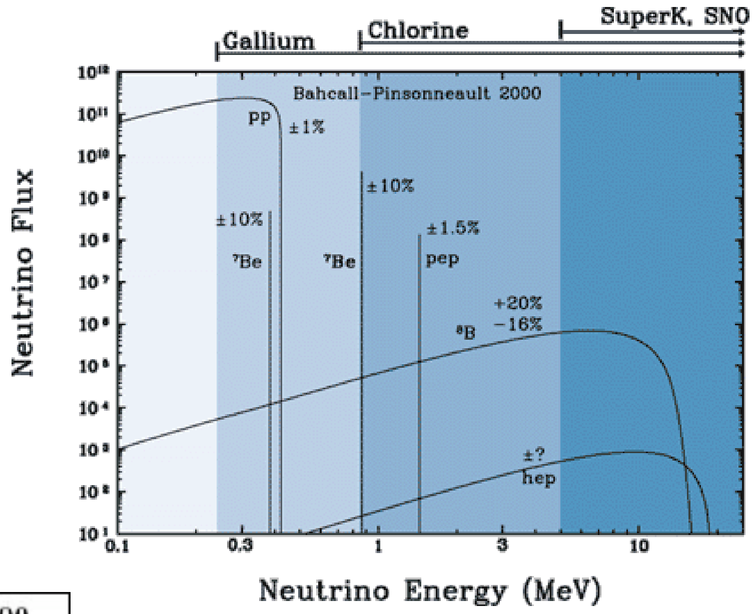
$4p + 2e \rightarrow 4He + 2\nu_e + 26.7$ MeV (pp chain)

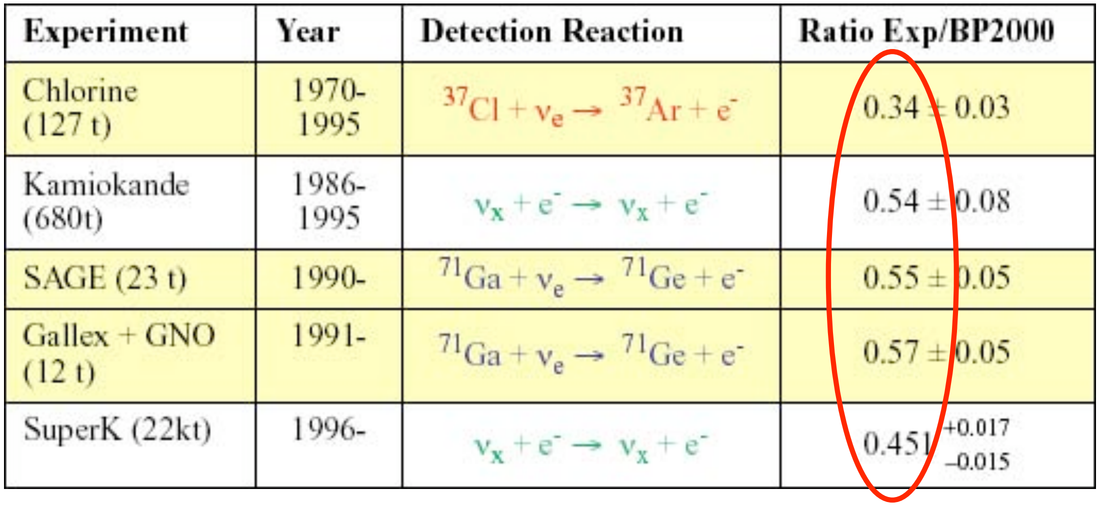
1960’s

- Ray Davis’ Chlorine detector
- First Solar Model calculations

For 30 years

CC and ES measurements of solar ν_e





Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$

(CC) $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

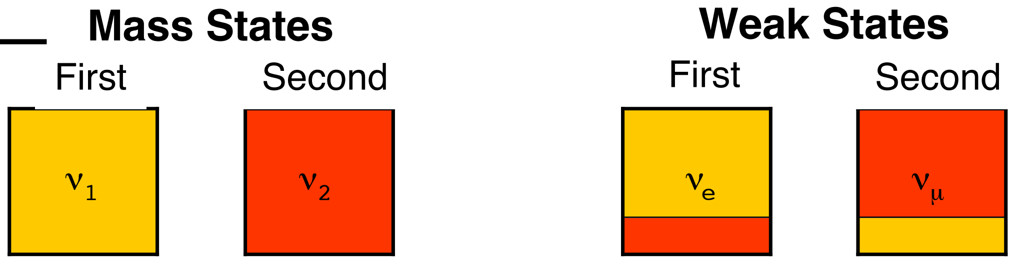
$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

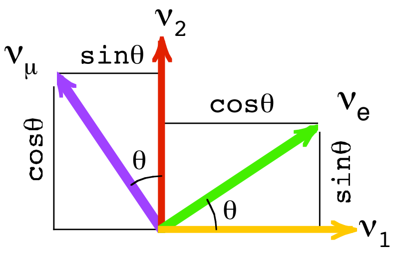
(ES) $\nu_x + e^- \rightarrow \nu_x + e^-$

→ Data are incompatible with solar models: Solar Neutrino Problem

Neutrino Oscillation

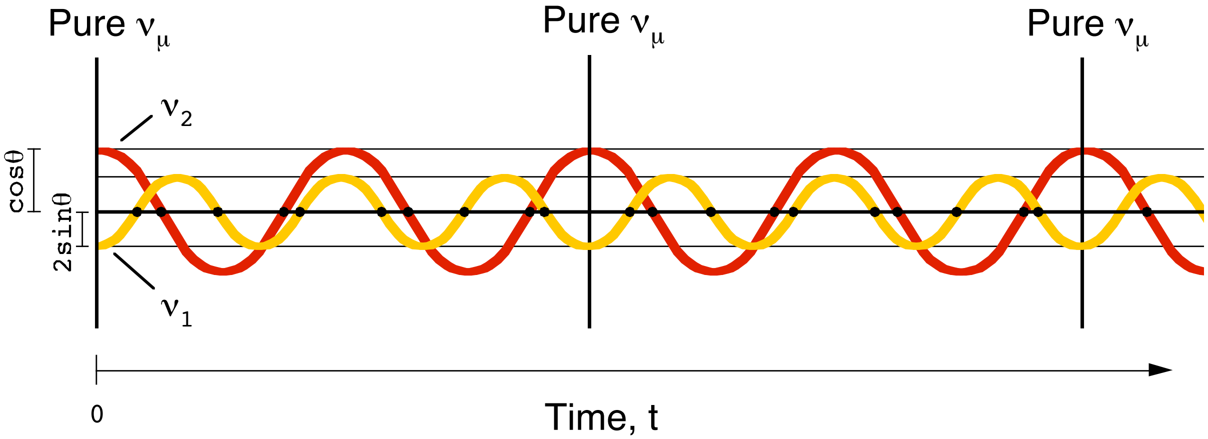
Neutrino States





$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ 2\sin\theta & \cos\theta \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

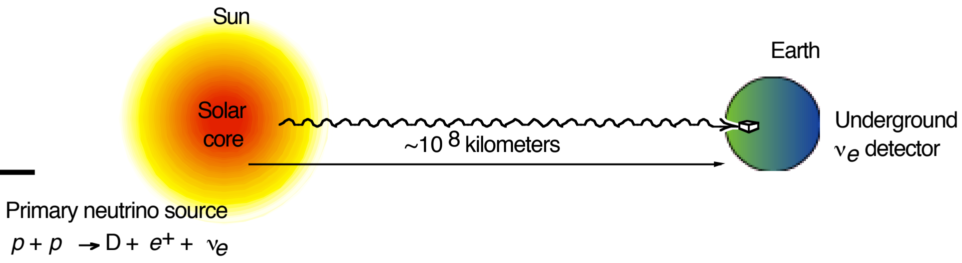
Time Evolution



$$P_{i\to i} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Oscillation as an indication of massive neutrinos

Experimental Studies



Natural Sources

The Sun

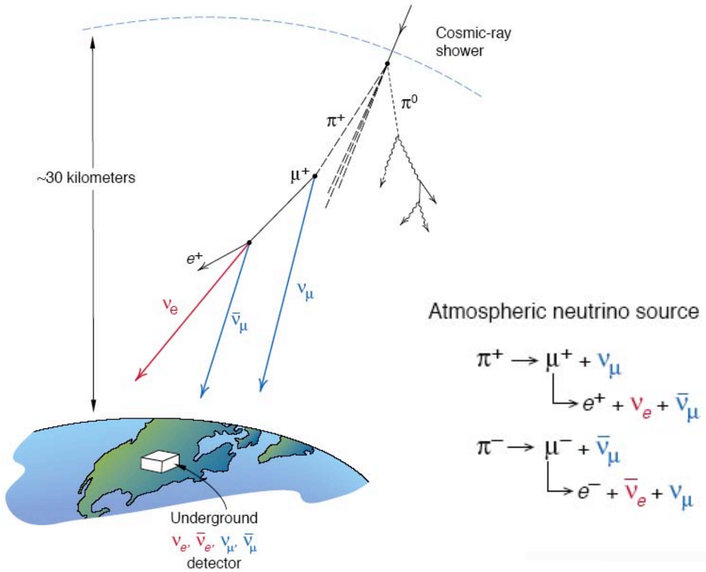
^{37}Cl
GALLEX
SAGE

Kamiokande
SuperKamiokande
SNO ★

Atmospheric Neutrinos

IMB
Soudan
MACRO

Kamiokande ★
SuperKamiokande
•••

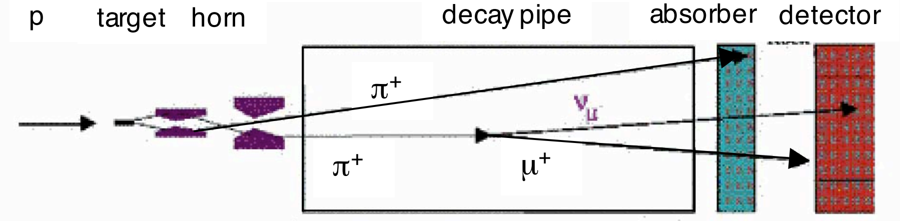


Man-Made Sources

Accelerators

K2K ★
Opera
. . .

Chorus
(LSND)

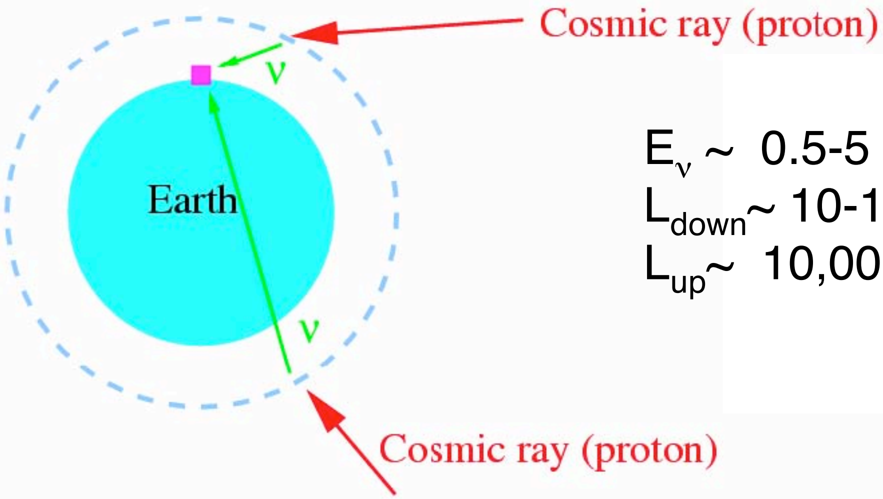


Nuclear Reactors

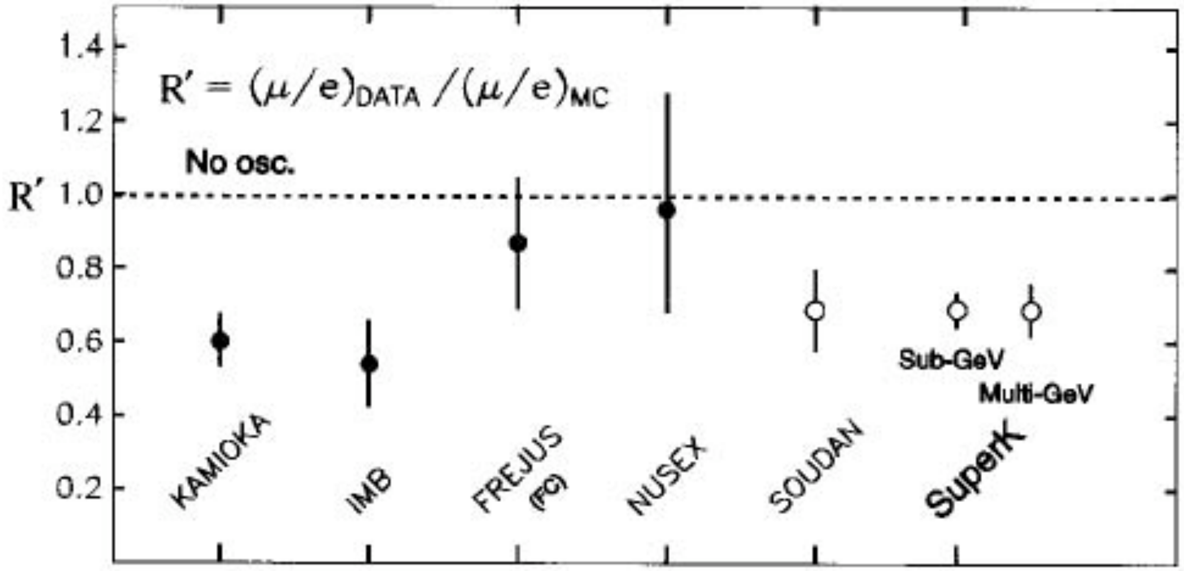
Bugey
ILL
Palo Verde

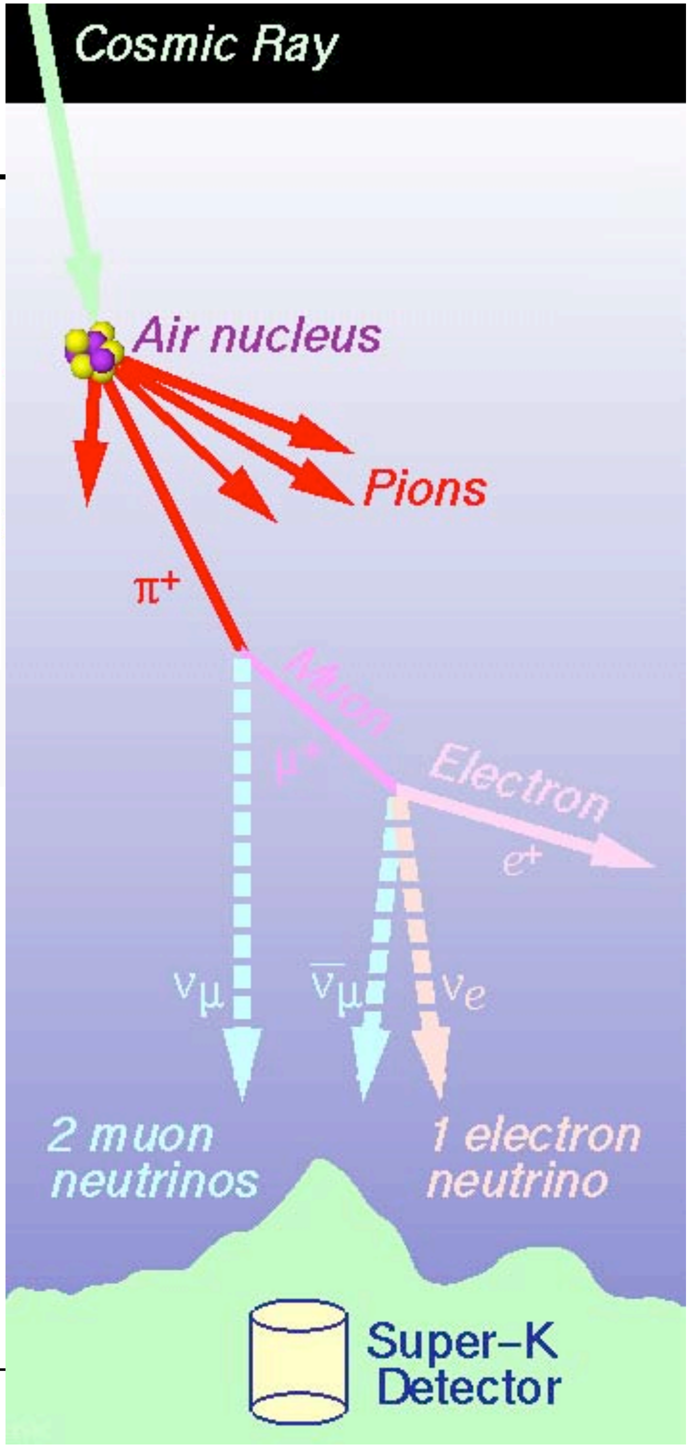
Goesgen
Chooz
KamLAND ★

Atmospheric Neutrino Studies



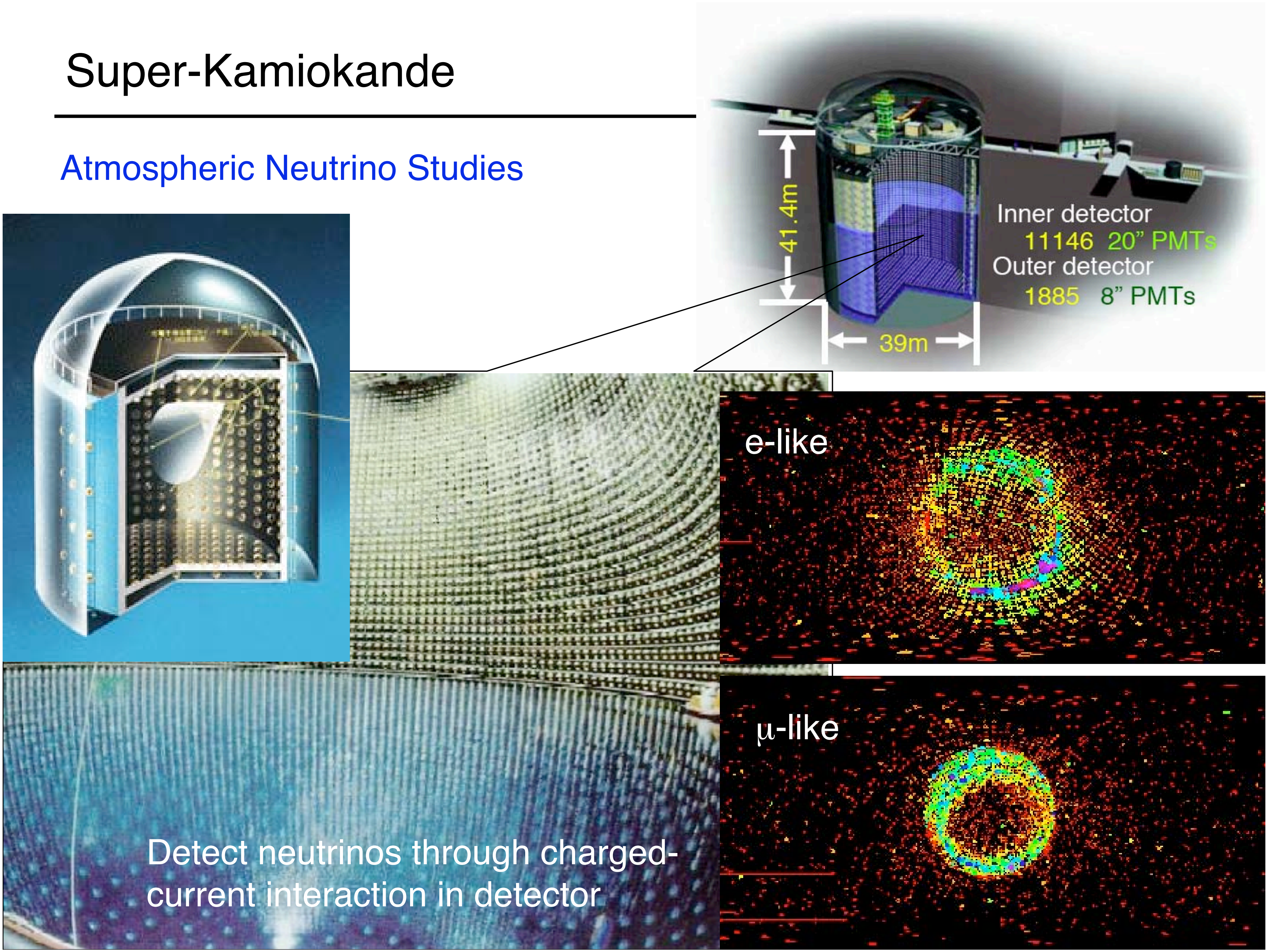
$E_\nu \sim$ 0.5-5 GeV
$L_{down} \sim$ 10-100 km
$L_{up} \sim$ 10,000 km





Super-Kamiokande

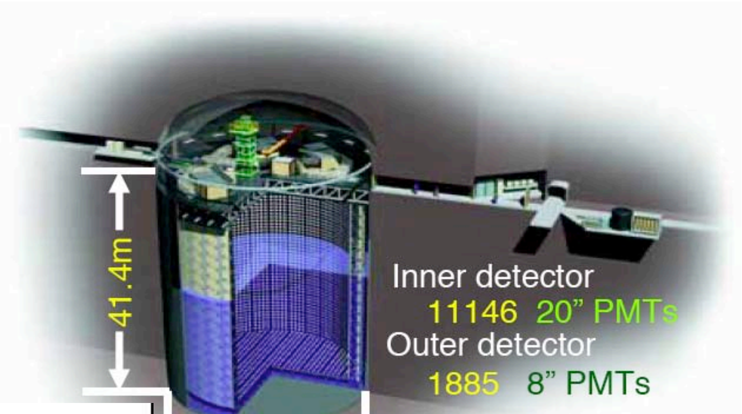
Atmospheric Neutrino Studies

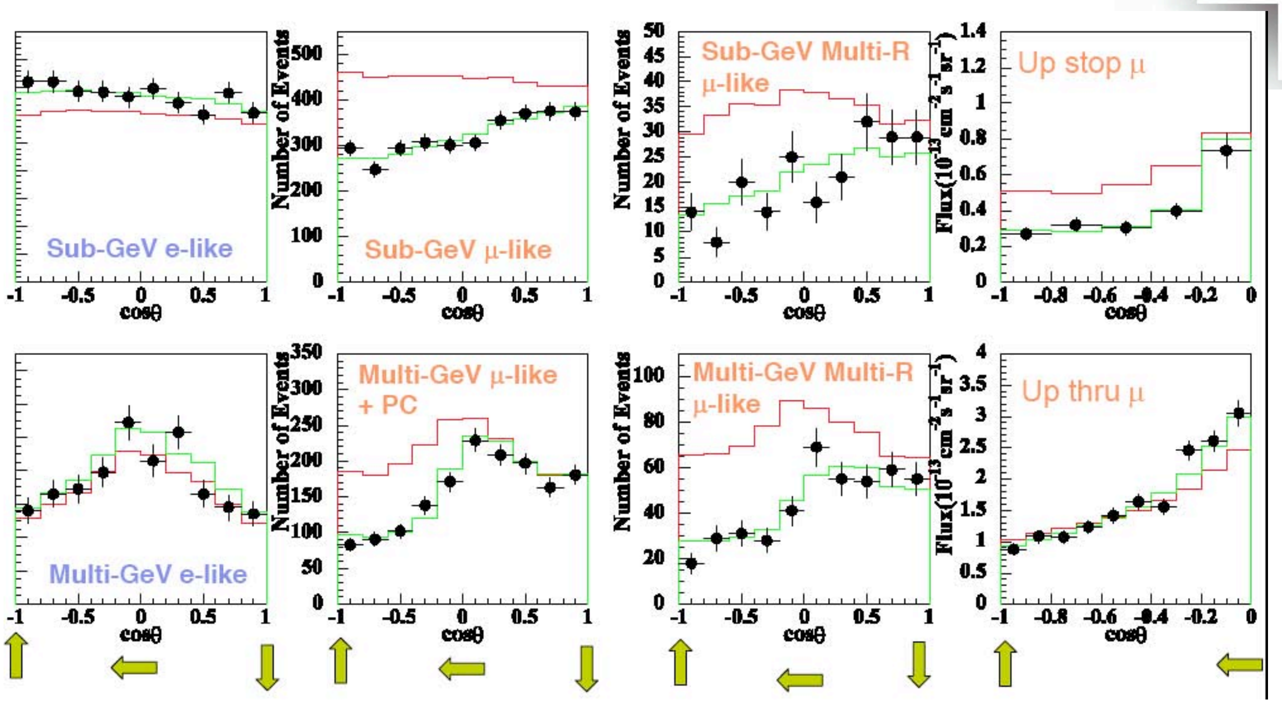


Detect neutrinos through charged-current interaction in detector

Super-Kamiokande

Atmospheric Neutrino Studies



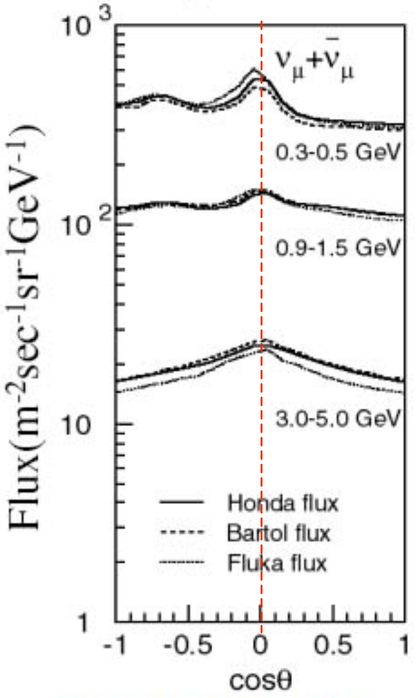


Deficit of upward-going ν_μ

🟩 **Best fit** $\nu_\mu \rightarrow \nu_\tau$ 2-flavor osc.
$\sin^2 2\theta=1.0$, $\Delta m^2=2.0\times10^{-3}$ eV^2

🟥 **Null oscillation**

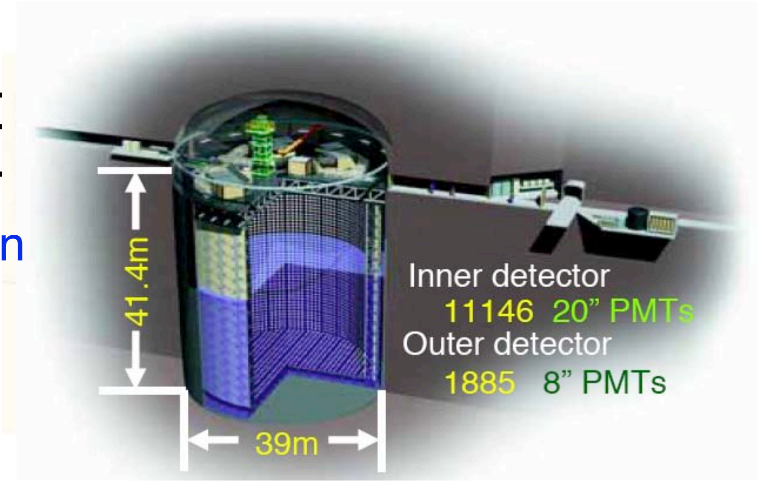
Zenith angle dist. of Atmospheric ν flux



Eν > a few GeV
Up/Down Symmetry

Karsten Heeger, LBNL

KEK to Kamioka (K2K) Experiment

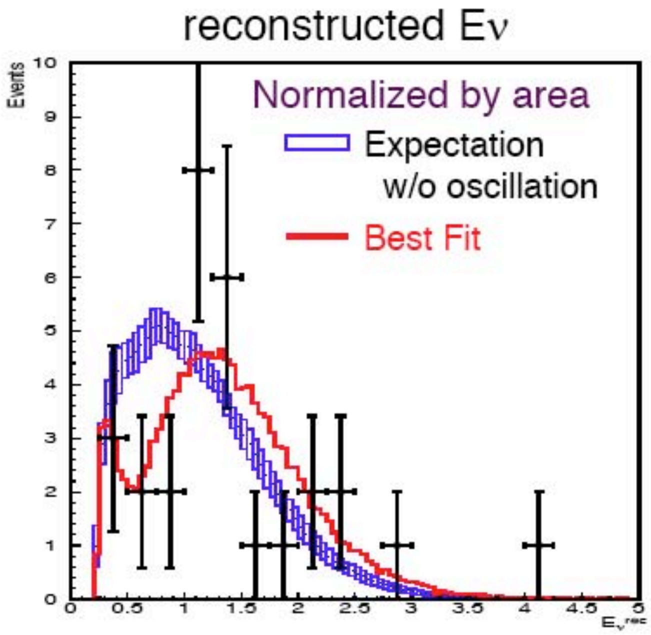


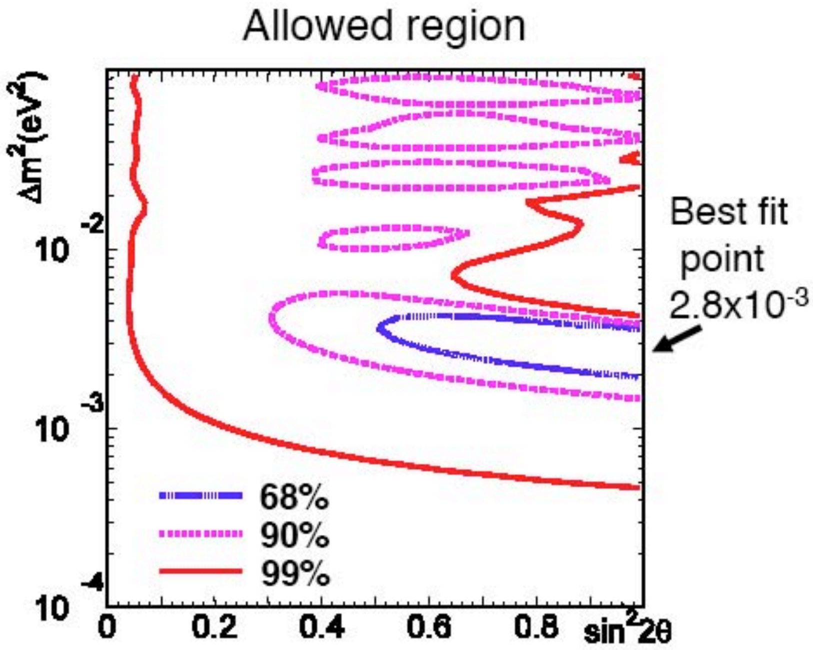
Accelerator-based long baseline neutrino oscillation experiment to test atmospheric oscillations

	atm	**K2K**
L	$10\text{-}10^4$ km	250 km
E_n	0.1~100 GeV	~ 1.3 GeV
Δm^2	$10^{-1}\sim10^{-4}$ eV^2	$> 2\times10^{-3}$ eV^2
ν_e/ν_μ	50%	~1%

data from 1999-2001

expected: 80.1 events
observed: 56 events

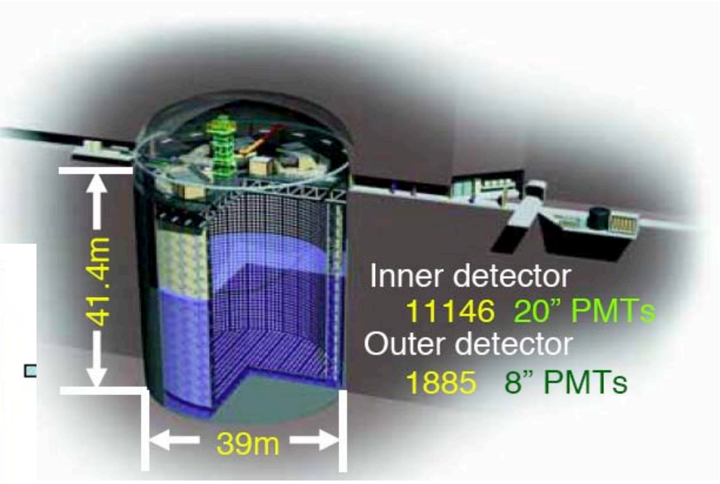




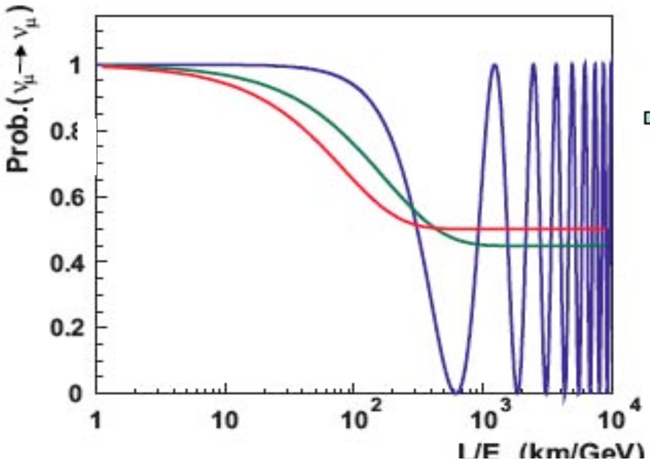
Best fit point 2.8×10^{-3}

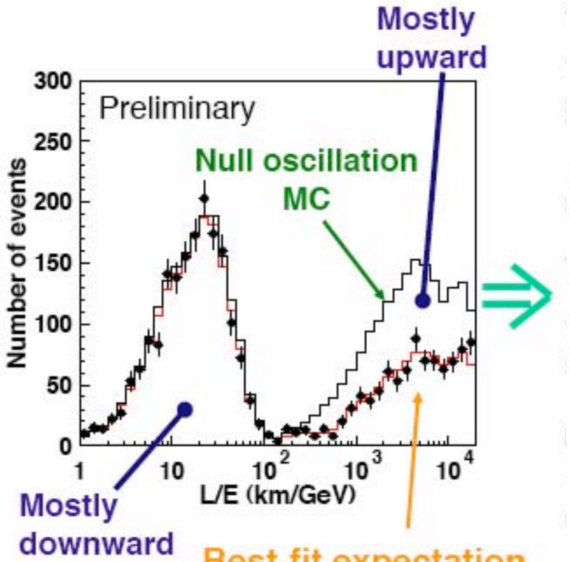
Super-Kamiokande L/E Analysis

Searching for Direct Evidence of Oscillations



Neutrino oscillation
Neutrino decay
Neutrino decoherence



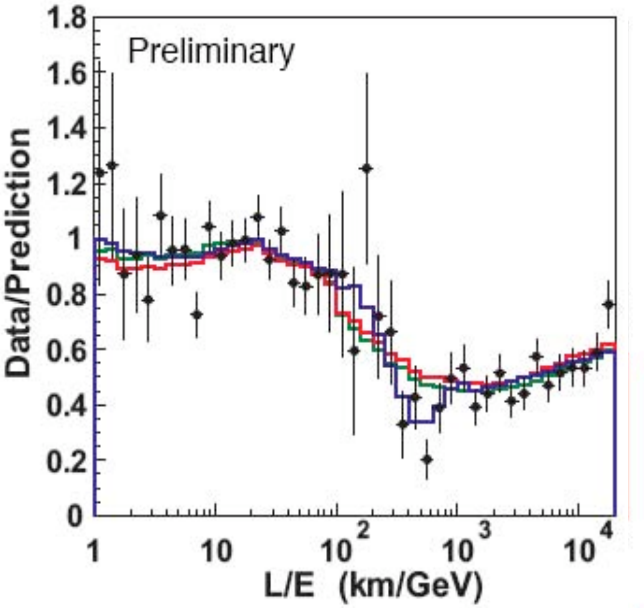


⇒

Best-fit expectation

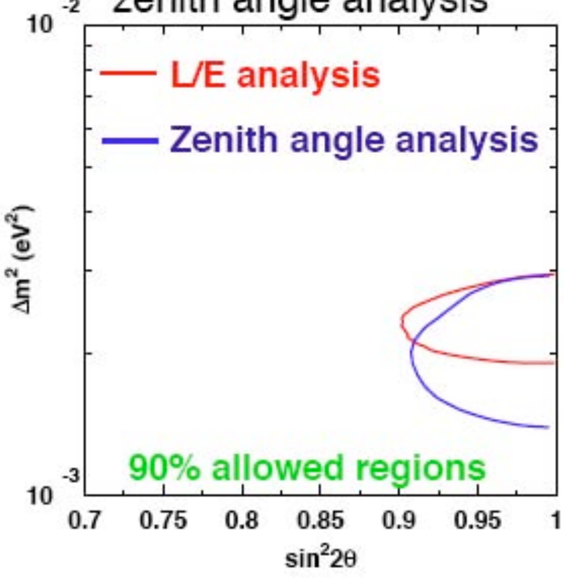
$\Delta m^2=2.4\times10^{-3}, \sin^2 2\theta=1.00$

$\chi^2_{min}=37.8/40$ d.o.f

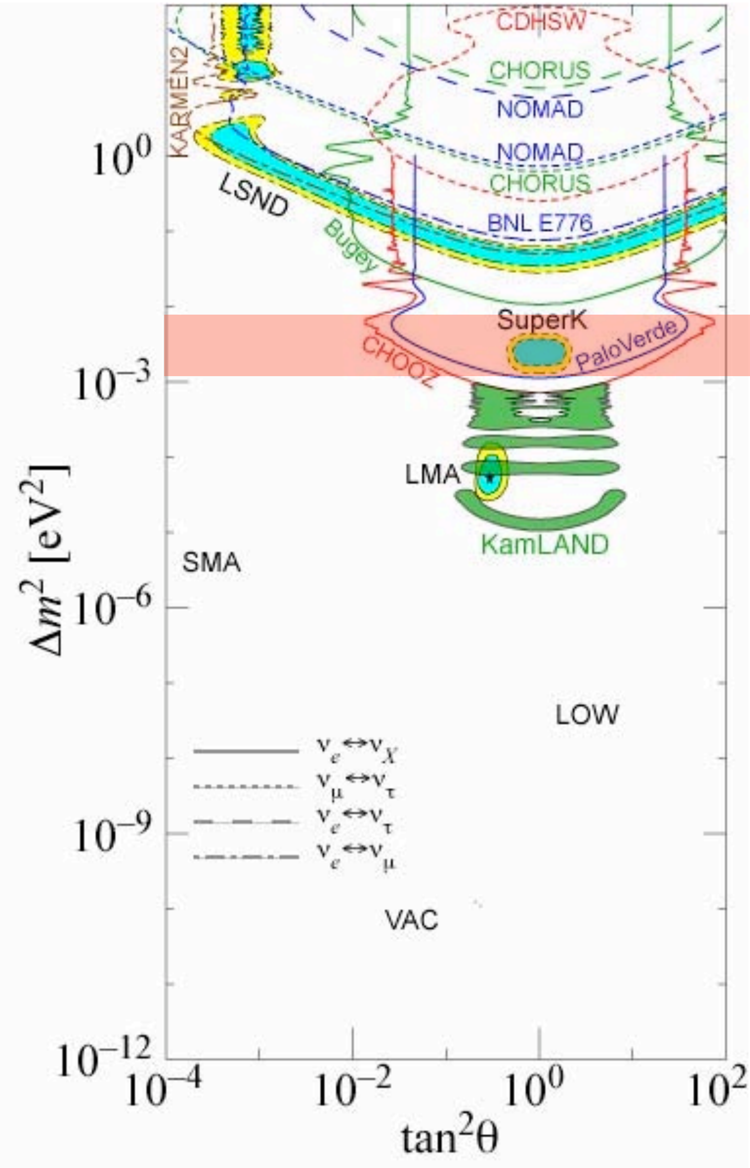


First dip is observed as expected from neutrino oscillation

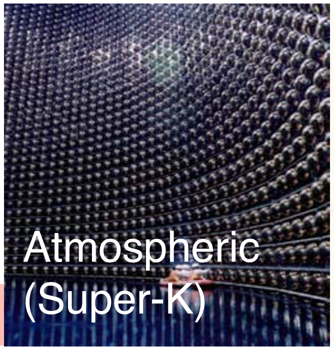
Consistent with standard zenith angle analysis



Atmospheric Neutrino Oscillations



$\nu_\mu \Rightarrow \nu_\tau$



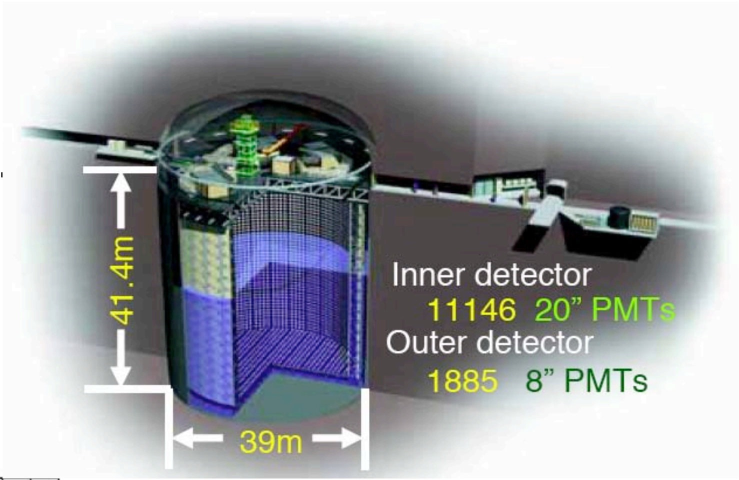
Atmospheric
(Super-K)

Accelerator
(K2K)

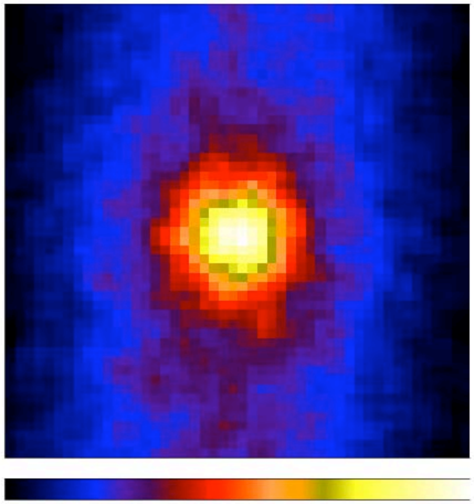
Atmospheric ν data explained extremely well by oscillations

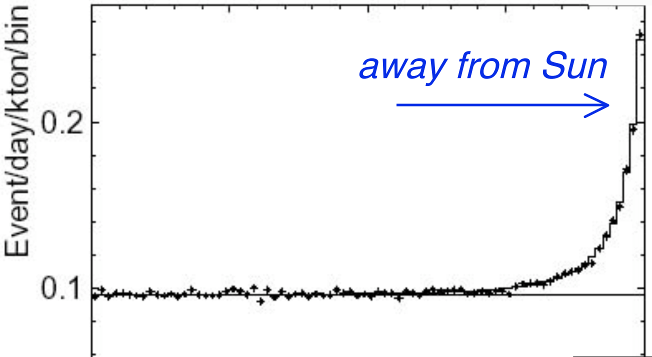
- primarily $\nu_\mu \rightarrow \nu_\tau$ conversion
- mixing angle θ_{23} is near maximal
- $\Delta m^2 \sim 2 \times 10^{-3}$ eV^2

High-Statistics Solar Neutrino Observations at Super-Kamiokande



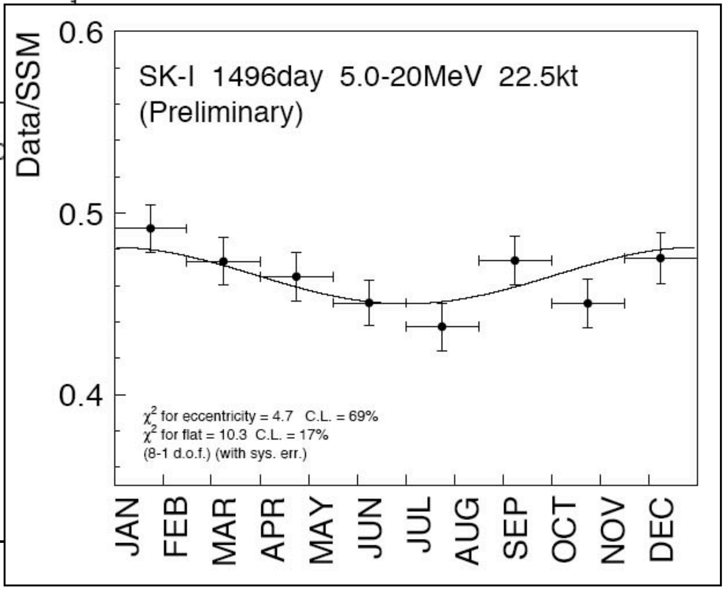
Elastic Scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$





Observing the neutrino Sun …

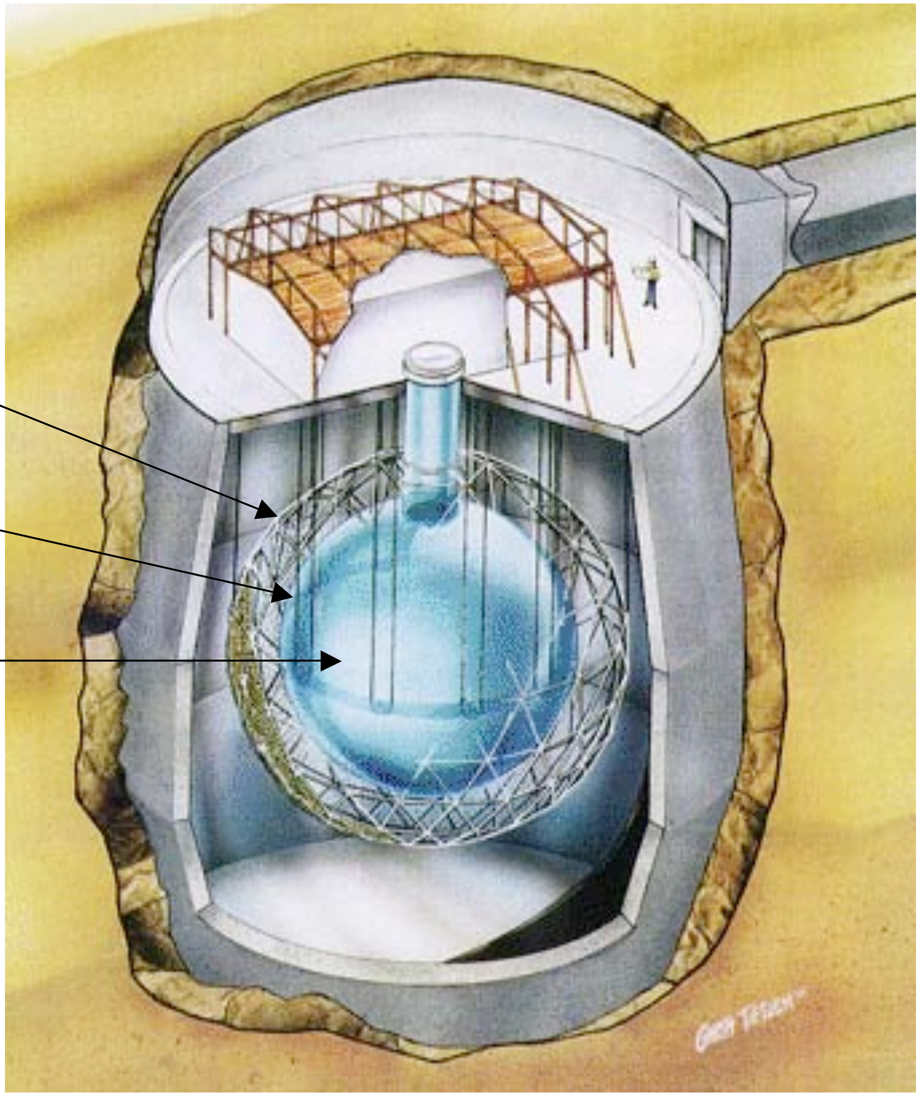
Seasonal Variation



$$\text{Data/SSM} = 0.451 \pm \underset{\text{(stat)}}{0.005} \; \underset{\text{(sys.)}}{{}^{+0.016}_{-0.014}}$$

Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.) ↑



PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

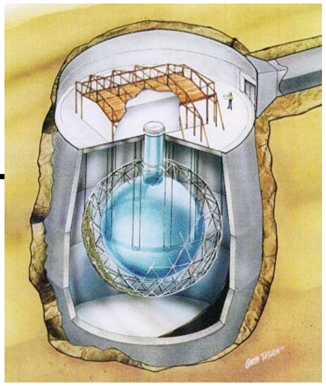
Acrylic Vessel, 12 m diameter

1000 Tonnes D_2O

Need solar model-independent measurement.

Need experiment that measures ν_e and $\nu_{\mu,\tau}$ separately.

Neutrino Detection in SNO



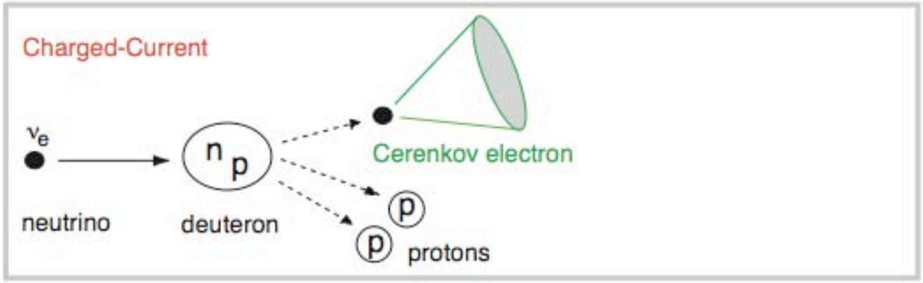
Neutrino Interactions on Deuterium and their Flavor Sensitivity

Charged-Current (CC)

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

$E_{thresh} = 1.4$ MeV

Measurement of energy spectrum

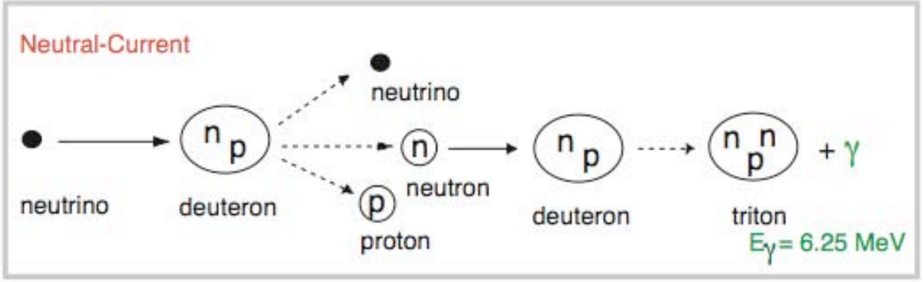


Neutral-Current (NC)

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

$E_{thresh} = 2.2$ MeV

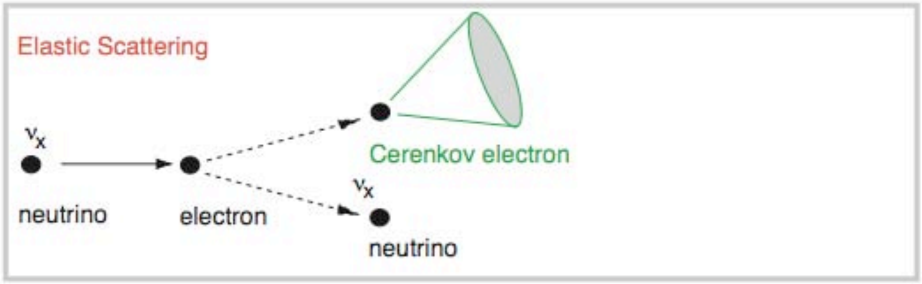
Measures total ^{8}B flux from Sun



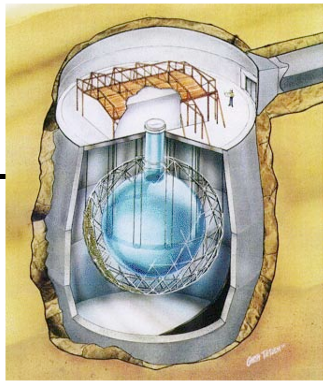
Elastic Scattering (ES)

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

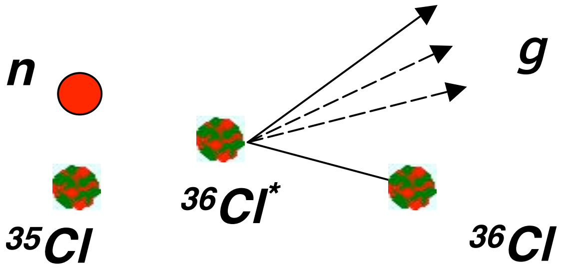
Strong directional sensitivity

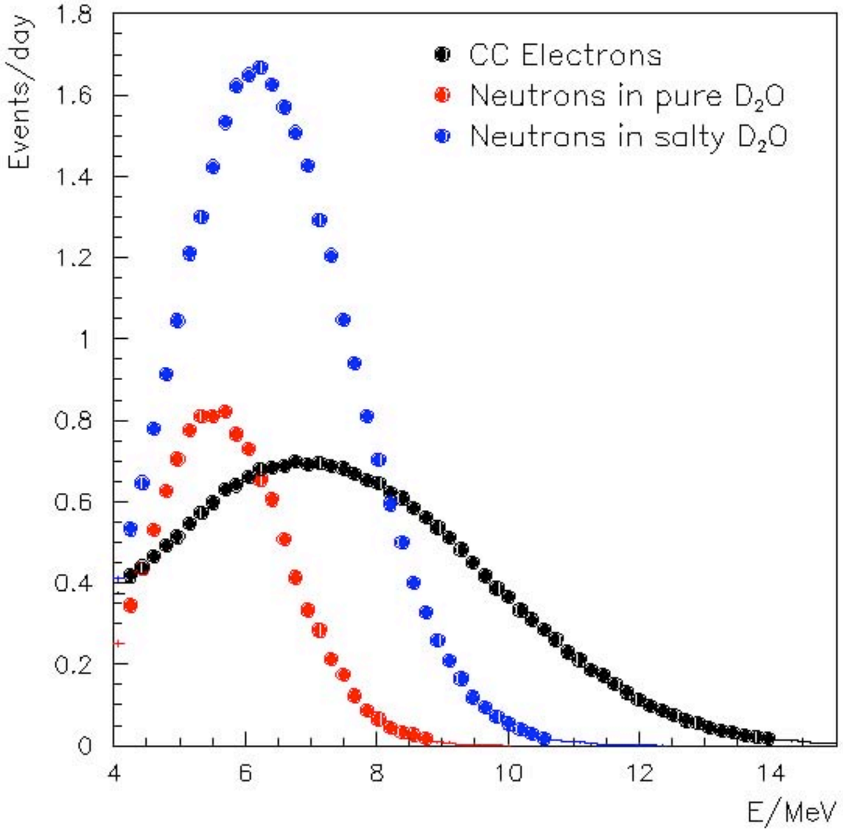


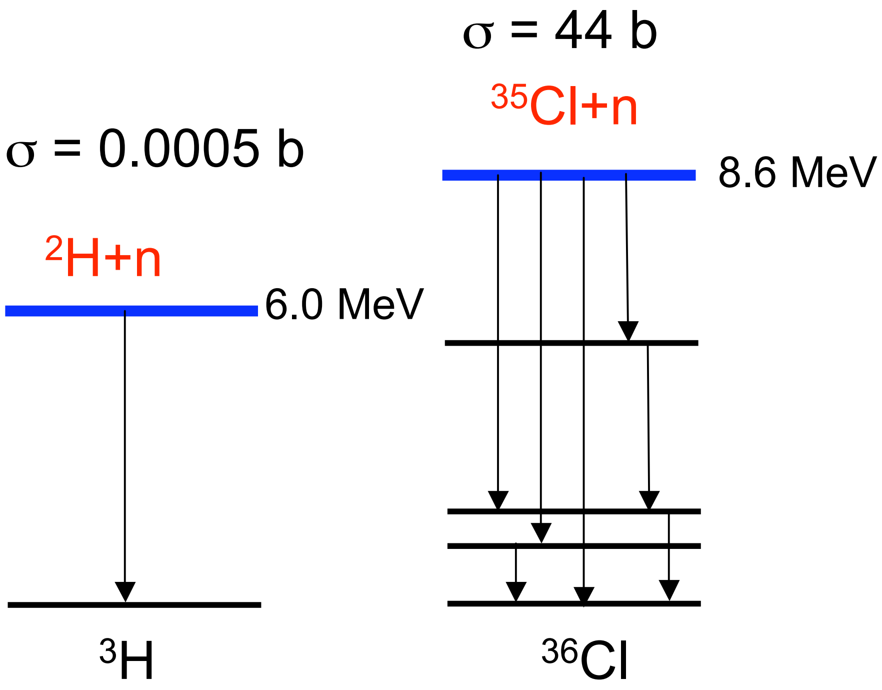
SNO - Enhanced Neutron Detection with NaCl



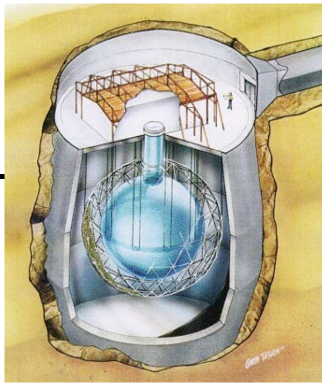
- Higher capture cross section
- Higher energy release
- Many gammas







Solar Neutrino Physics with SNO



What can we learn from measuring the NC interaction rate (total active ^{8}B solar neutrino flux) at SNO?

- Total ^{8}B ν flux (NC) *versus* ν_e flux (CC)

$$\frac{[CC]}{[NC]} = \frac{[\nu_e]}{[\nu_e + \nu_\mu + \nu_\tau]}$$

→ Test of neutrino flavor change

- Total flux of solar ^{8}B neutrinos

→ Test of solar models

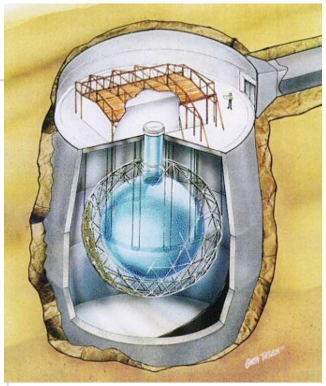
- Diurnal time dependence

→ Test of neutrino oscillations

- Distortions of neutrino energy spectrum

→ Test of neutrino oscillations

SNO Signal Extraction

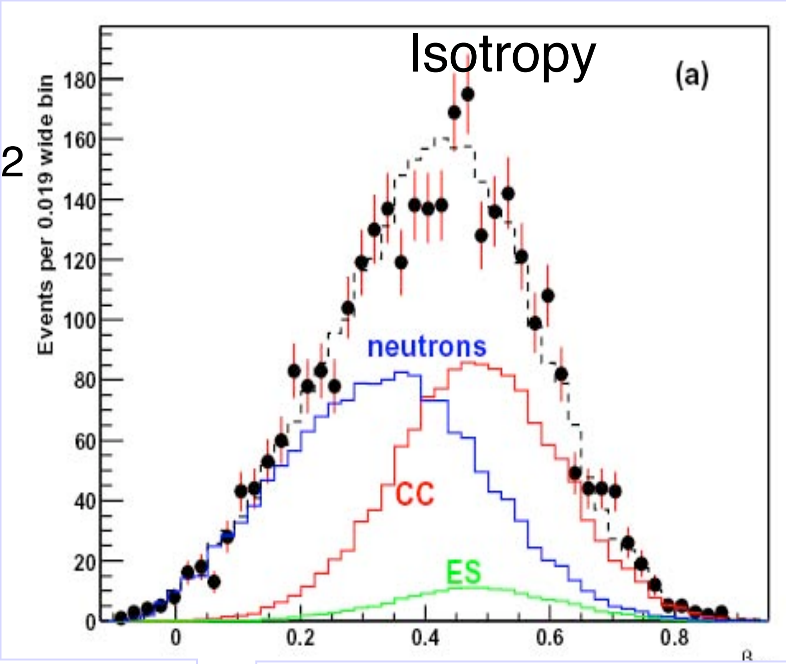


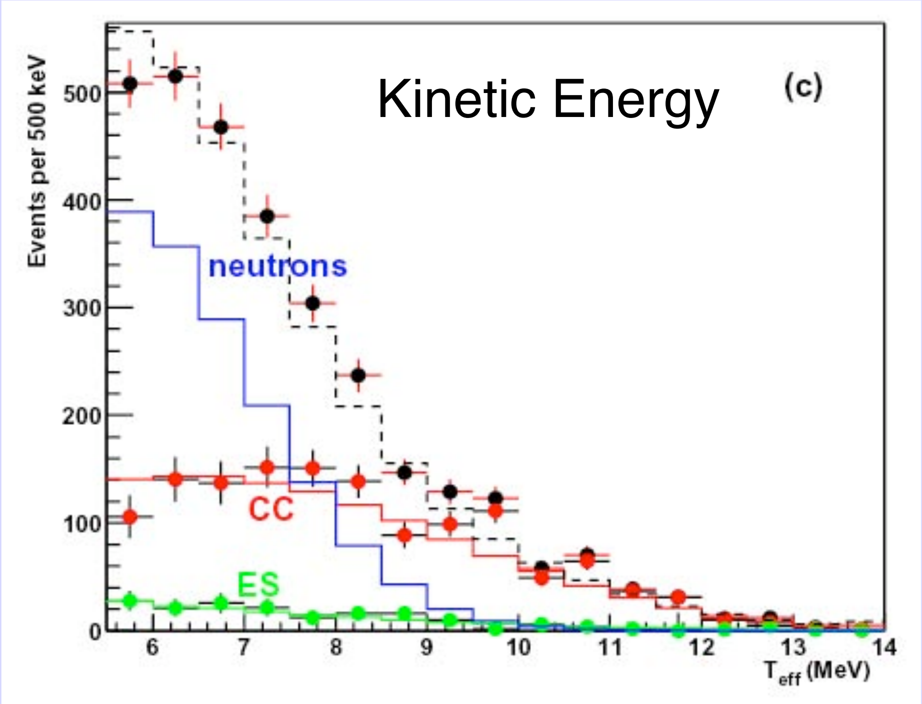
Data from July 26, 2001 to Oct. 10, 2002

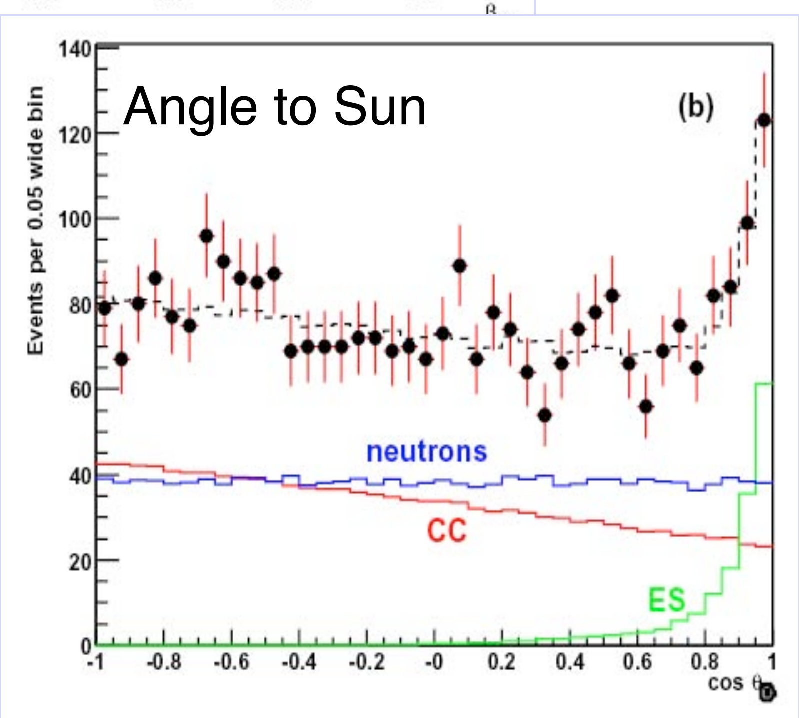
254.2 live days
Blind analysis performed

3055 candidate events:

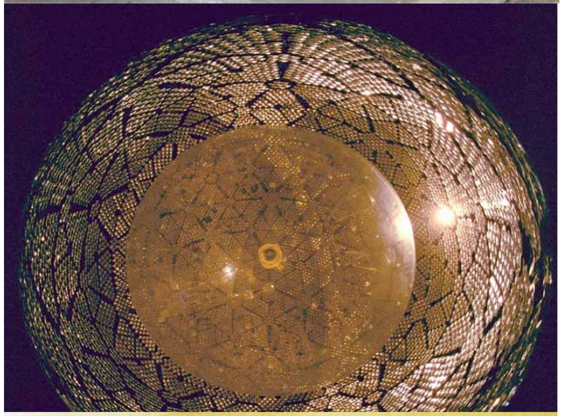
$1339.6^{+63.8}_{-61.5}$ CC
$1344.2^{+69.8}_{-69.0}$ NC
$170.3^{+23.9}_{-20.1}$ ES

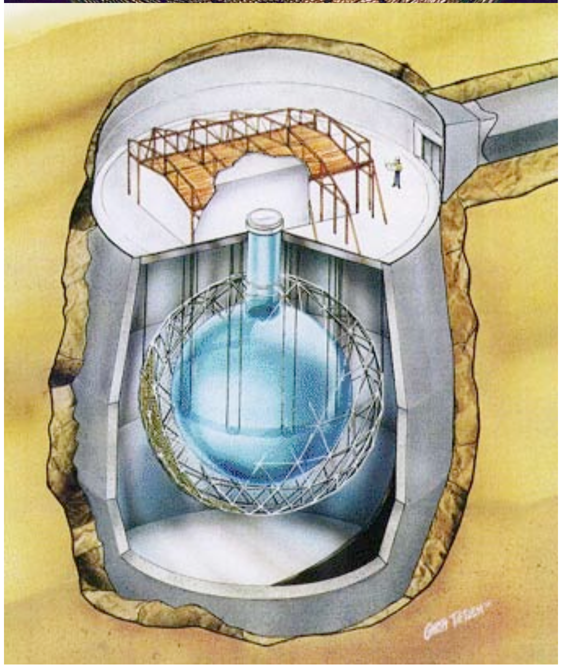

Isotropy

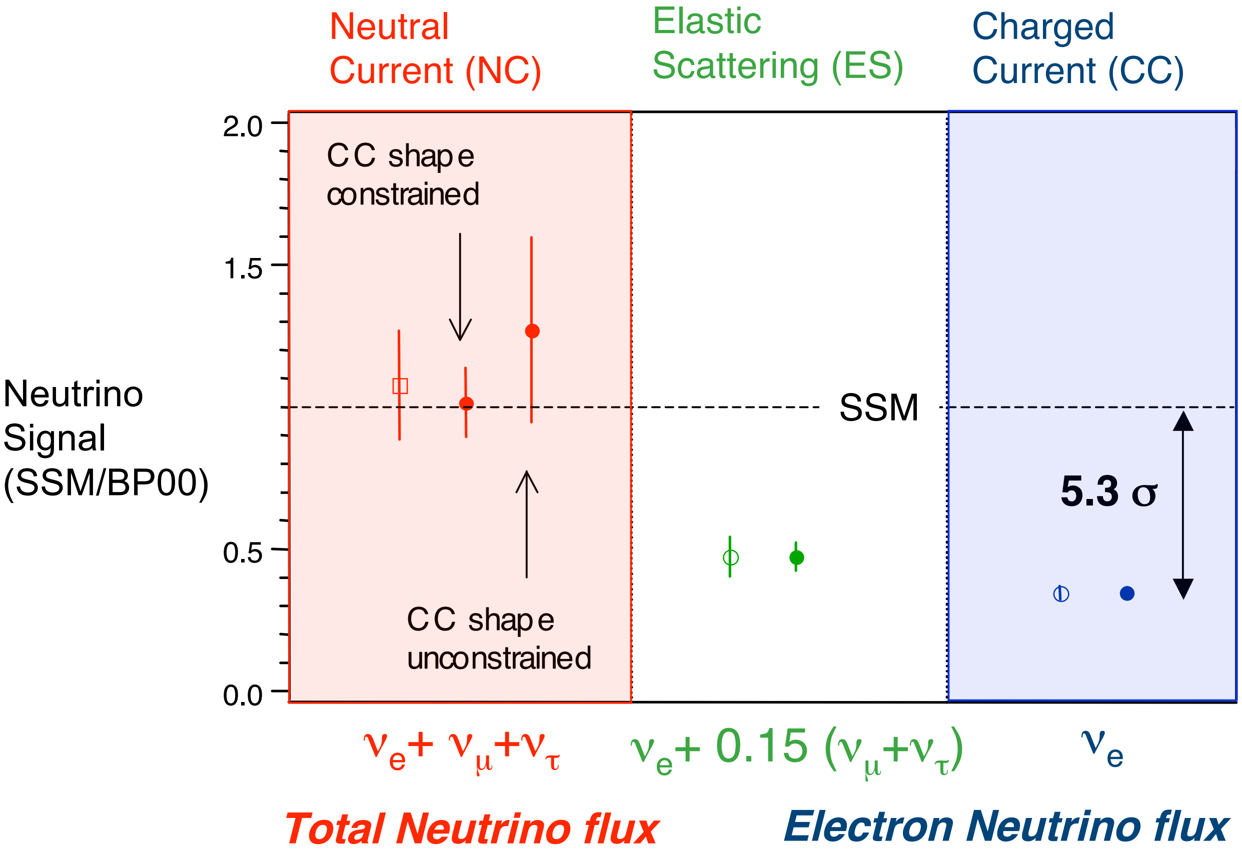

Kinetic Energy


Angle to Sun

The Solution to the Solar Neutrino Problem: Neutrinos Change Flavor



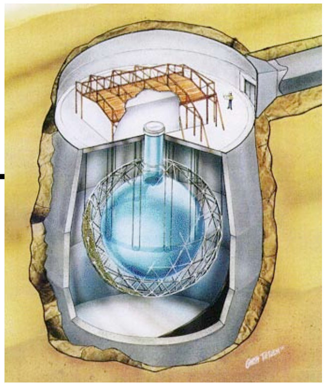




Results from SNO, 2002

2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$

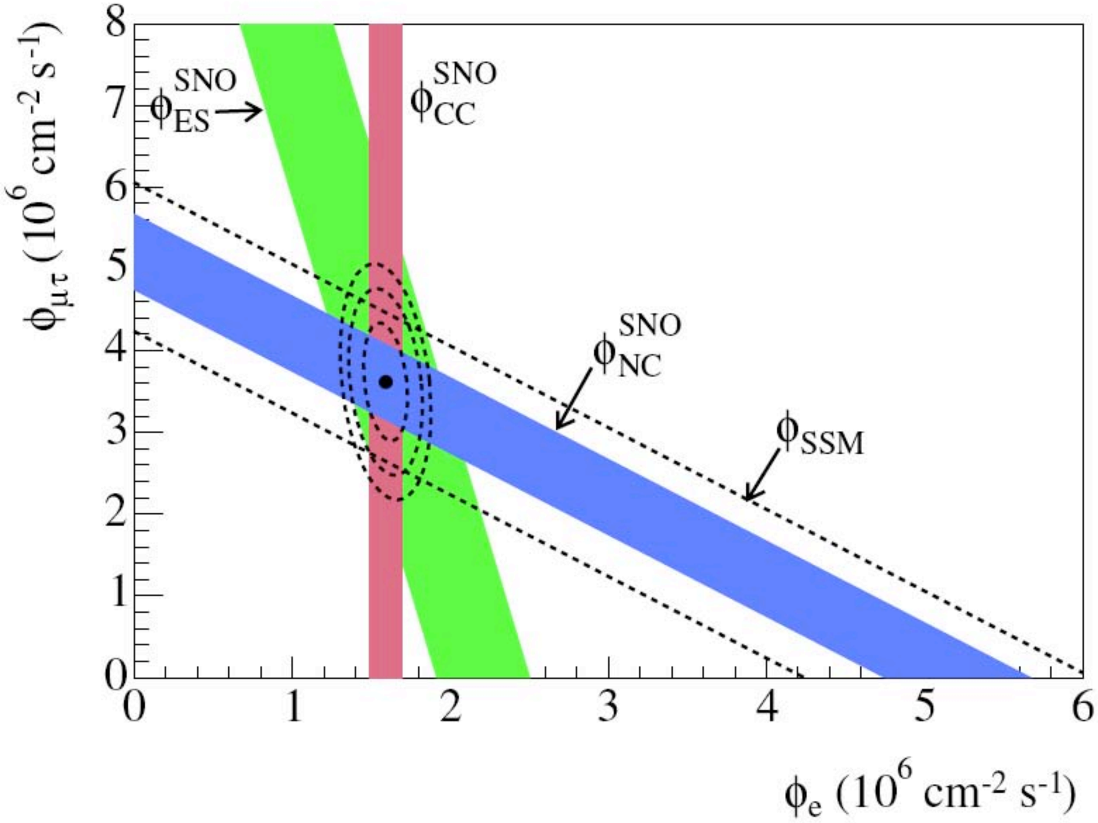
Flavor Content of ^{8}B Solar Neutrino Flux



^{8}B Standard Solar Model (SSM01)	5.05 x 10^6 cm^{-2} s^{-1}
NC Salt Constrained	4.90 ± 0.38 x 10^6 cm^{-2} s^{-1}
NC Salt Unconstrained	5.21 ± 0.47 x 10^6 cm^{-2} s^{-1}

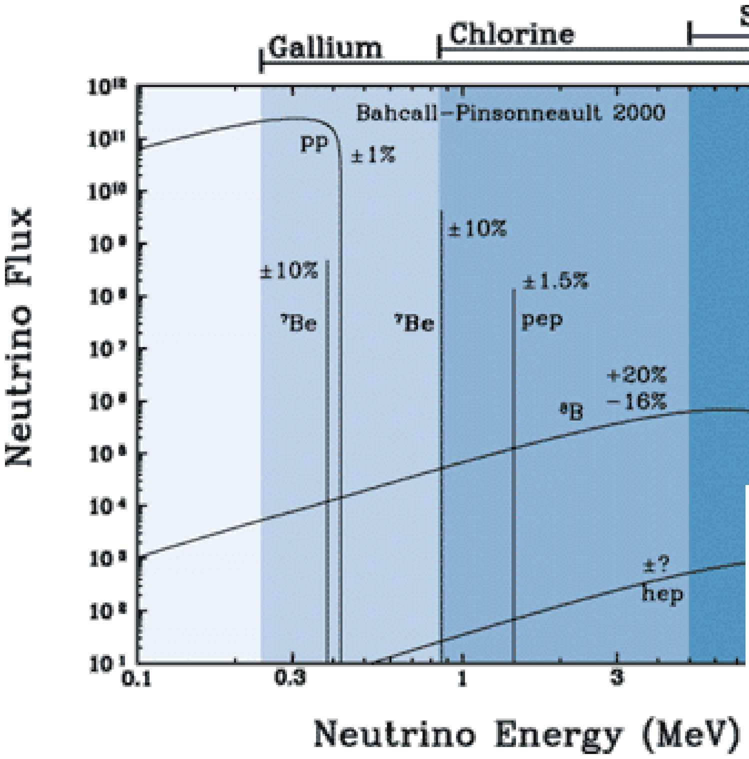
CC/NC Ratio

0.306 ± 0.026 (stat) ± 0.024 (sys)



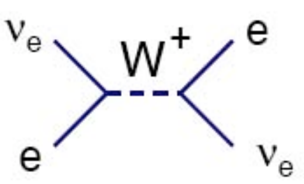
Standard Solar Model predictions for total ^{8}B flux in excellent agreement!

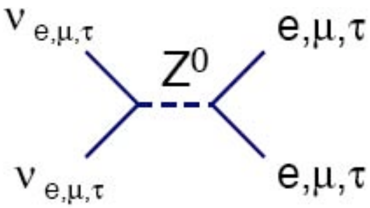
Oscillation Interpretation of Solar Neutrino Data



Energy-dependent effect

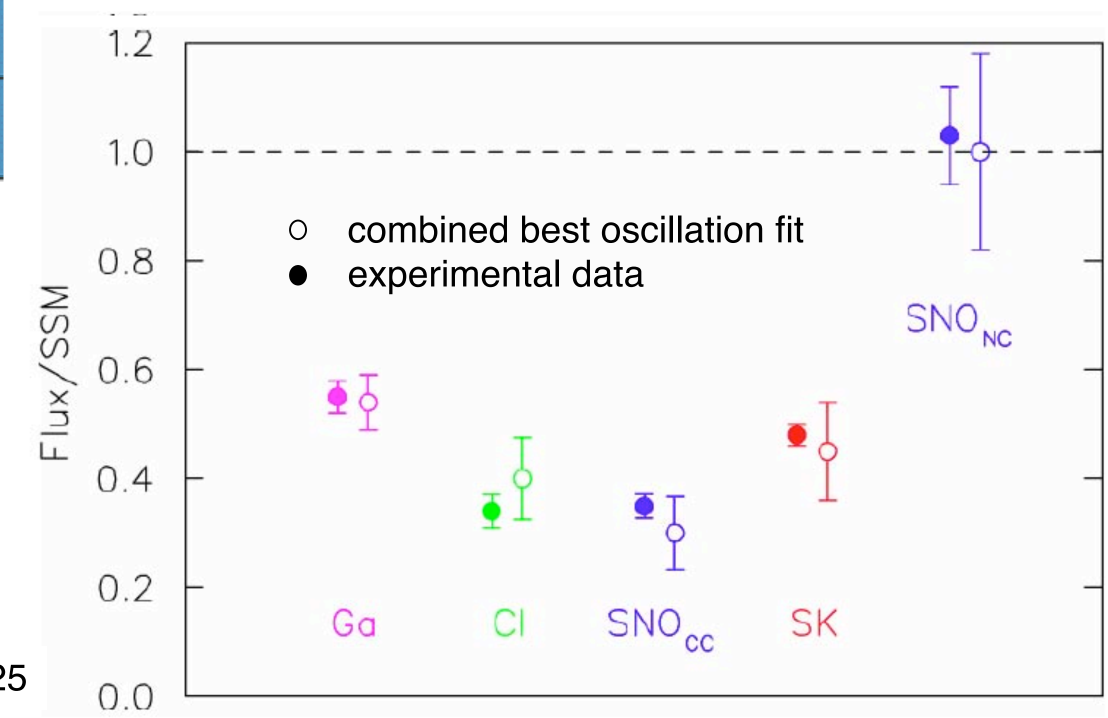
Neutrinos interact with matter in Sun and Earth (MSW)



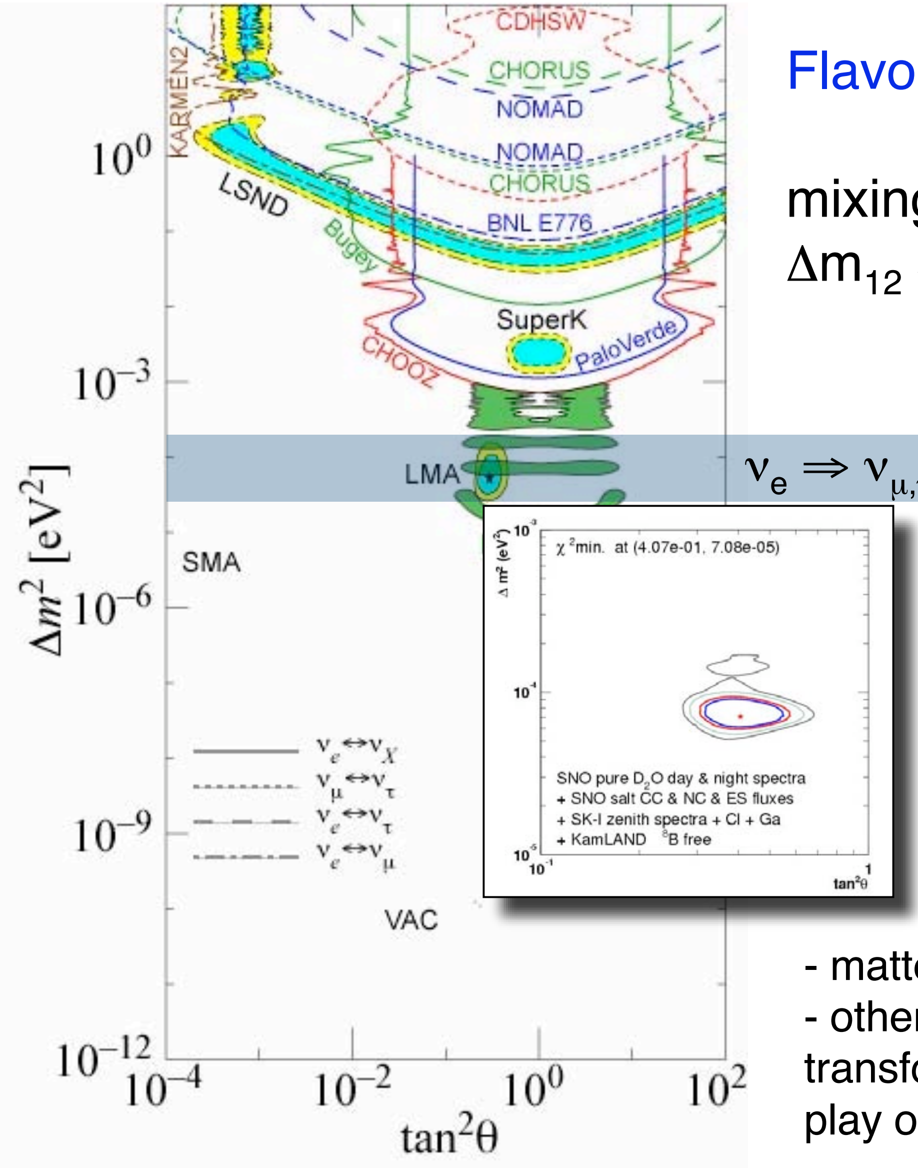


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{23} \times U_{13} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

hep-ph/0402025



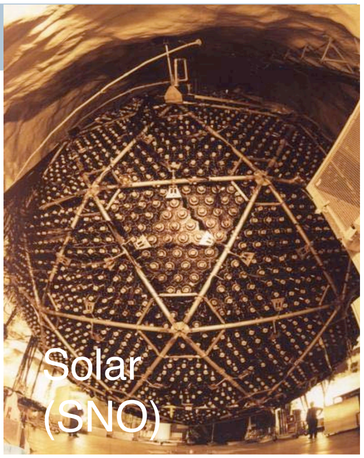
Solar Neutrino Oscillations



Flavor conversion of solar $\nu_e \rightarrow \nu_{\mu,\tau}$

mixing angle θ_{12} is large but not maximal,
$\Delta m_{12} \sim 7 \times 10^{-5}$ eV^2

$\nu_e \Rightarrow \nu_{\mu,\tau}$



- matter effects enhance oscillation
- other modes for solar neutrino flavor transformation (sterile, RSFP, CPT …) can play only a subdominant role.

Neutrino Oscillation Experiments

Reactor and Beamstop Neutrinos

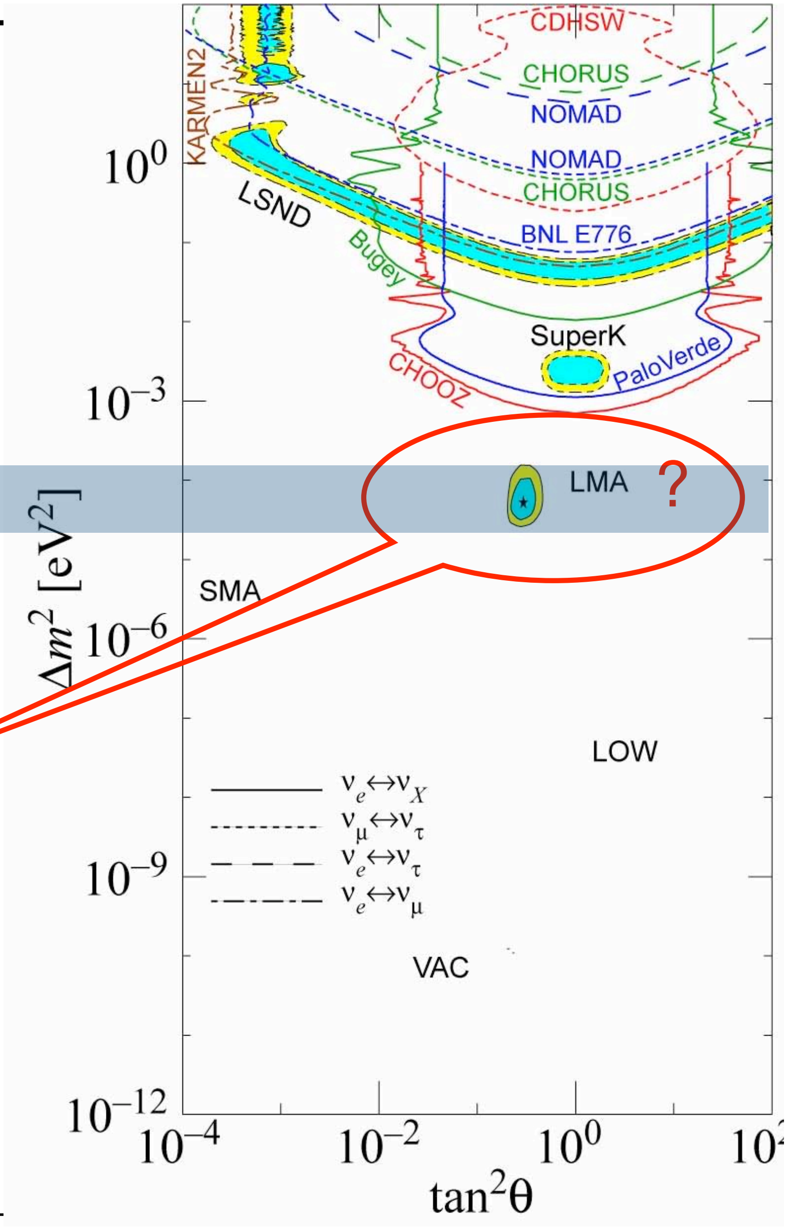
$\nu_\mu \Rightarrow \nu_s \Rightarrow \nu_e$

Atmospheric and Reactor Neutrinos

$\nu_\mu \Rightarrow \nu_\tau$

Solar and Reactor Neutrinos

$\nu_e \Rightarrow \nu_{\mu,\tau}$



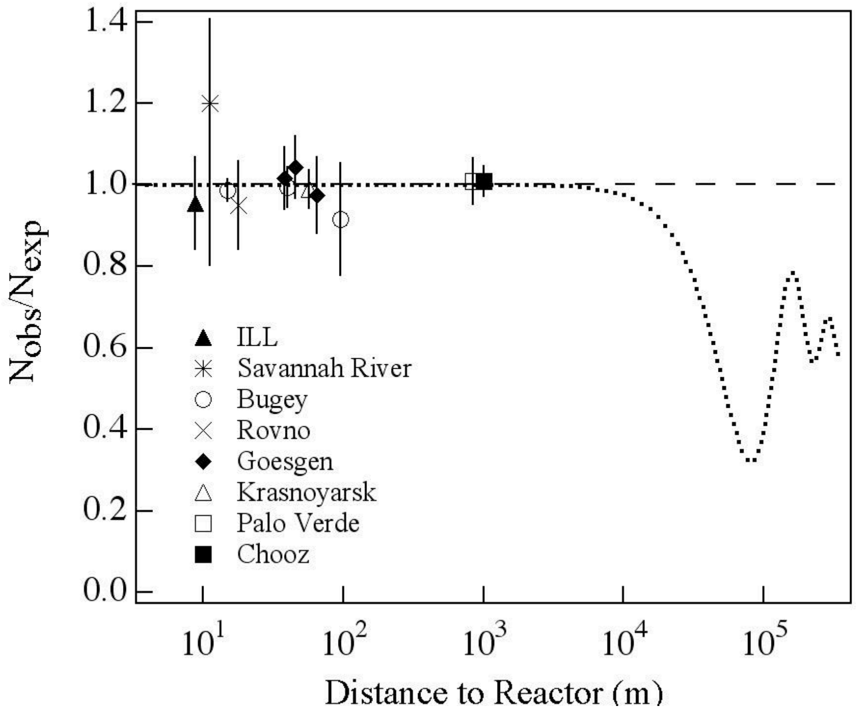
$\nu_e \Rightarrow \nu_{\mu,\tau}$

Large mixing favored

***LMA** solution can be tested with reactor neutrinos*

Status: Summer 2002

Search for Neutrino Oscillations with Reactor Neutrinos



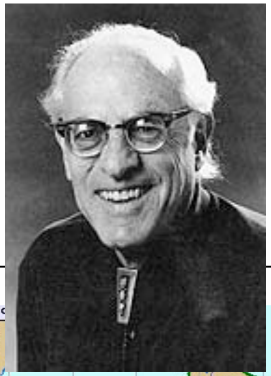
50 Years of Reactor Neutrino Physics

1953 First reactor neutrino experiment

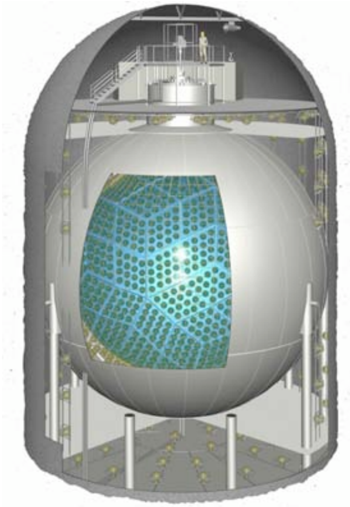
1956 *"Detection of Free Antineutrino"*, Reines and Cowan

→ Nobel Prize in 1995

No signature of neutrino oscillations until 2002!

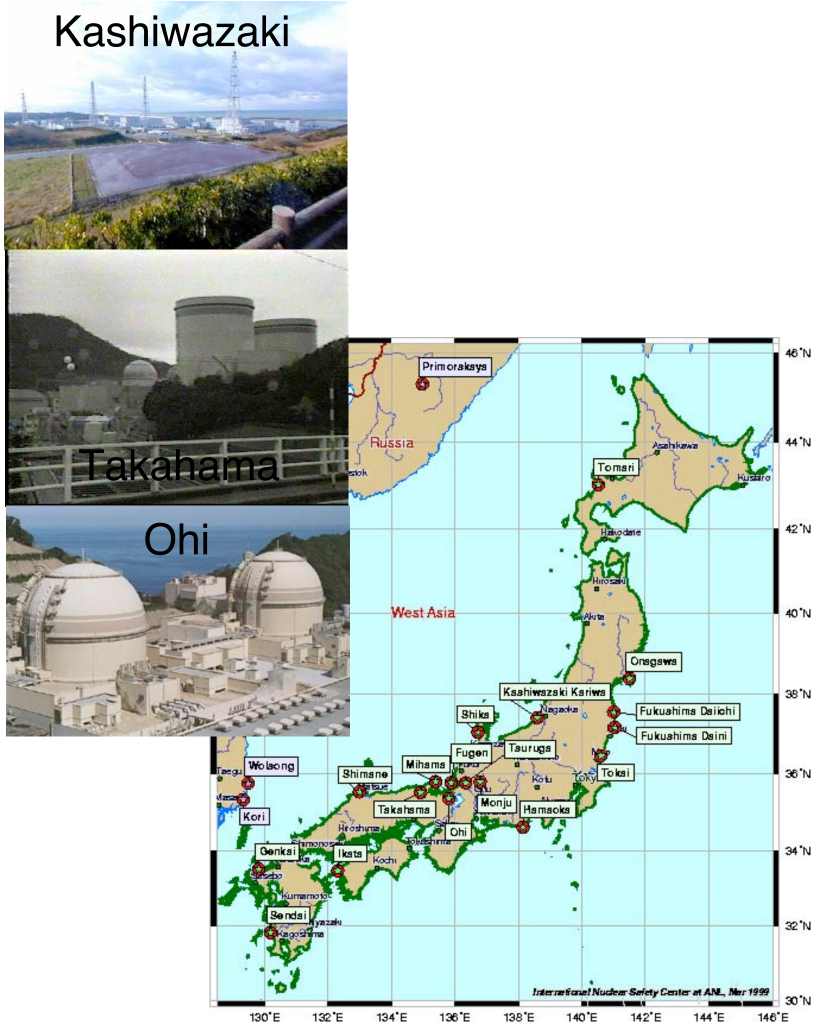


Results from solar experiments suggest study of reactor neutrinos with a baseline of ~ 70 km

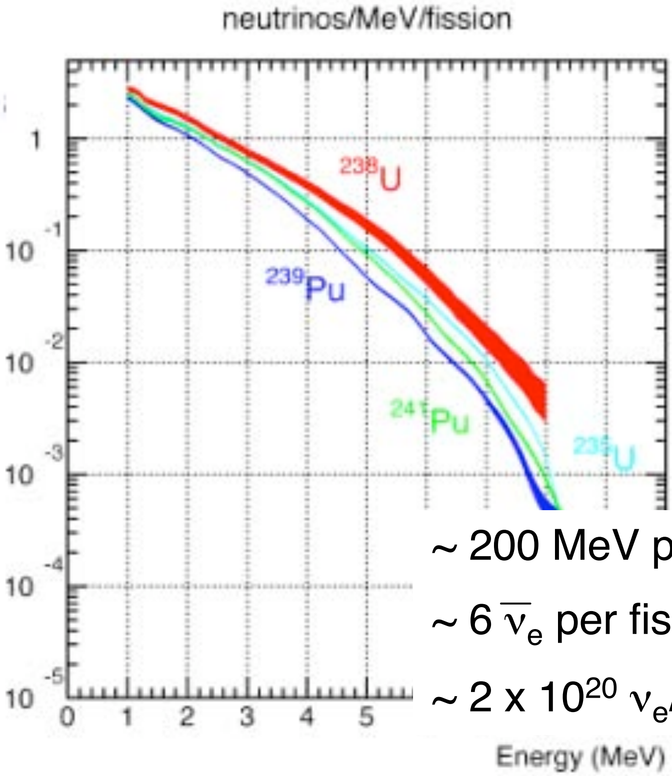


Reactor Antineutrinos

From Japanese Reactors



Spectrum from Principal Reactor Isotopes

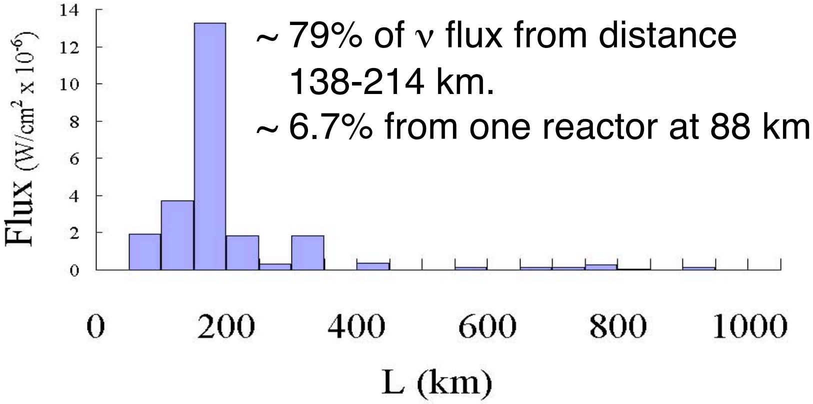


~ 200 MeV per fission

~ 6 $\overline{\nu}_e$ per fission

~ 2 x 10^{20} ν_e/GW_{th}-sec

Neutrino Flux at KamLAND



~ 79% of ν flux from distance 138-214 km.

~ 6.7% from one reactor at 88 km.

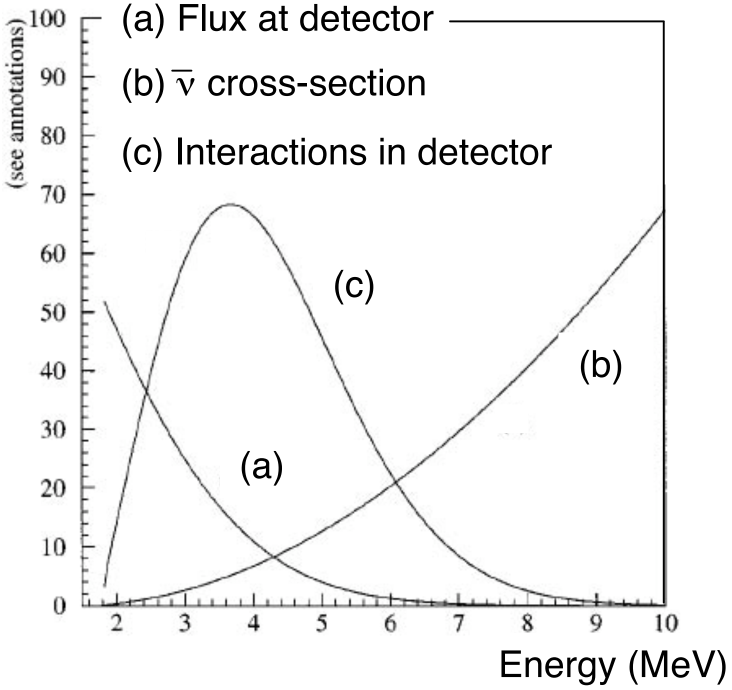
KamLAND - Kamioka Liquid Scintillator Antineutrino Detector

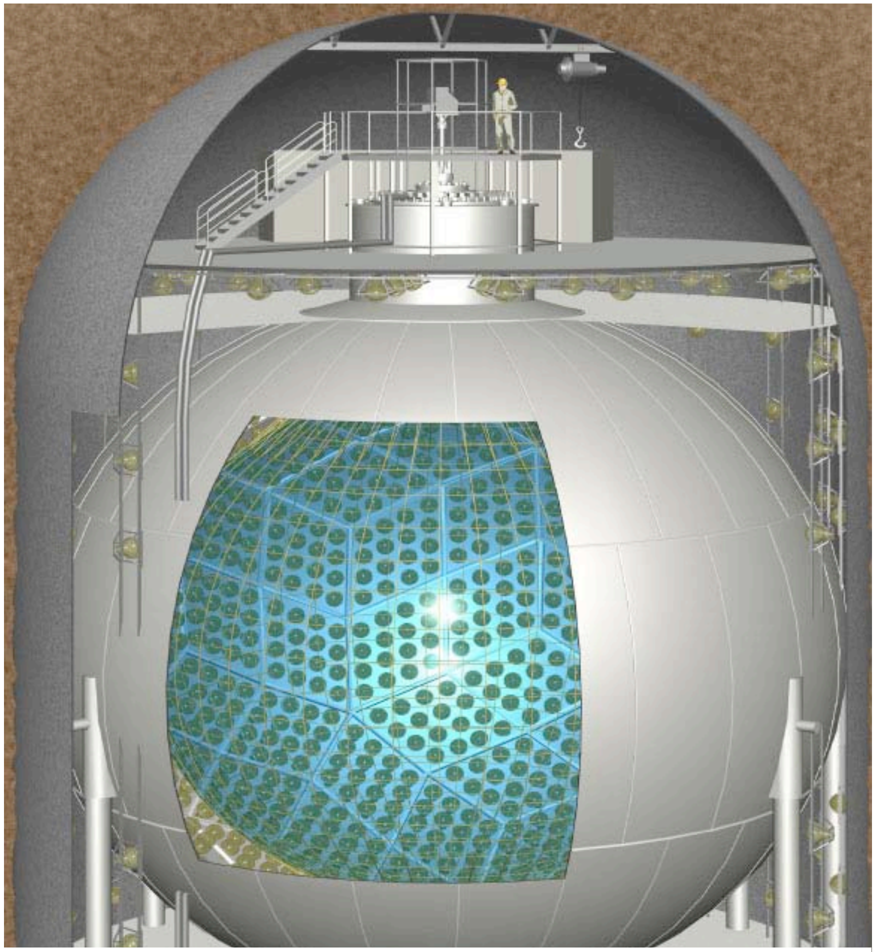
Uses reactor neutrinos to study $\overline{\nu}$ oscillation with a baseline of L ~ 140-210 km

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

Prompt e^+ annihilation

Delayed n capture, ~ 190 μs capture time



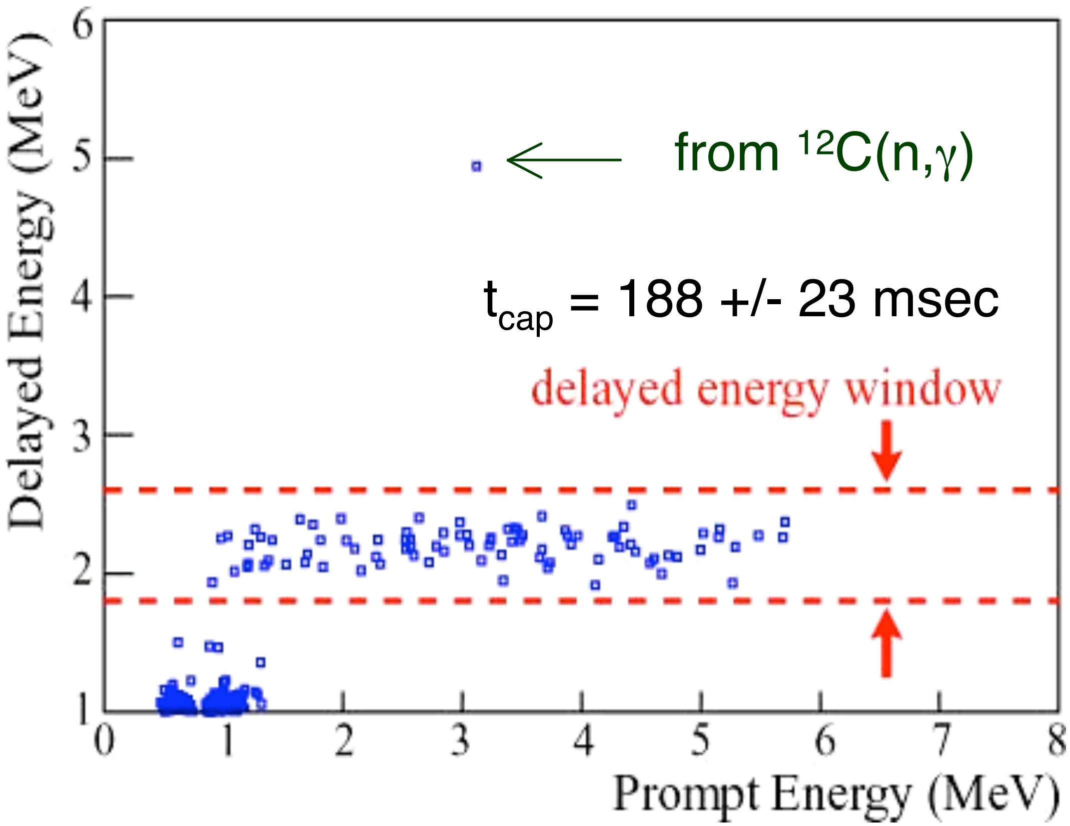


KamLAND studies the disappearance of $\overline{\nu}_e$ and measures

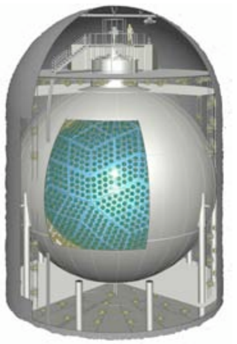
- interaction rate
- energy spectrum

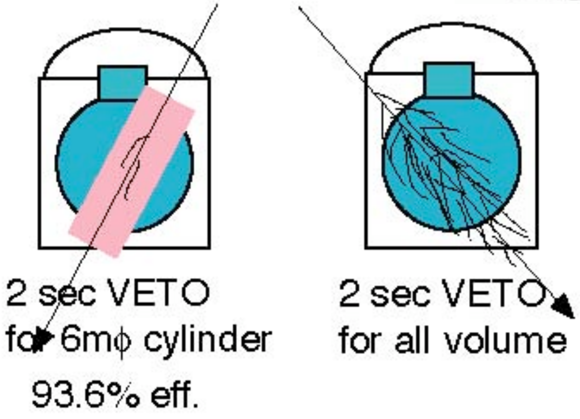
Event Selection

Delayed Energy Window



Muon veto





Vertex and Time Correlation

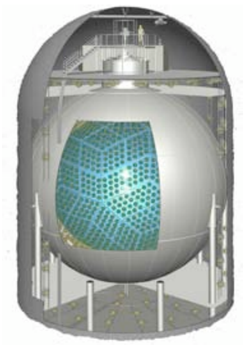
$R < 5$ m

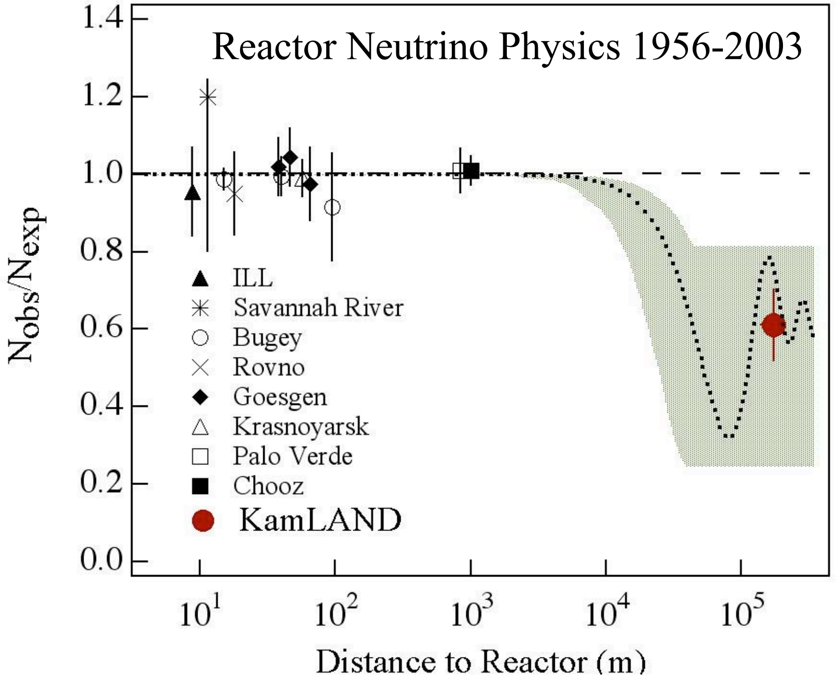
$0.5 < |dT| < 660\ \mu sec$

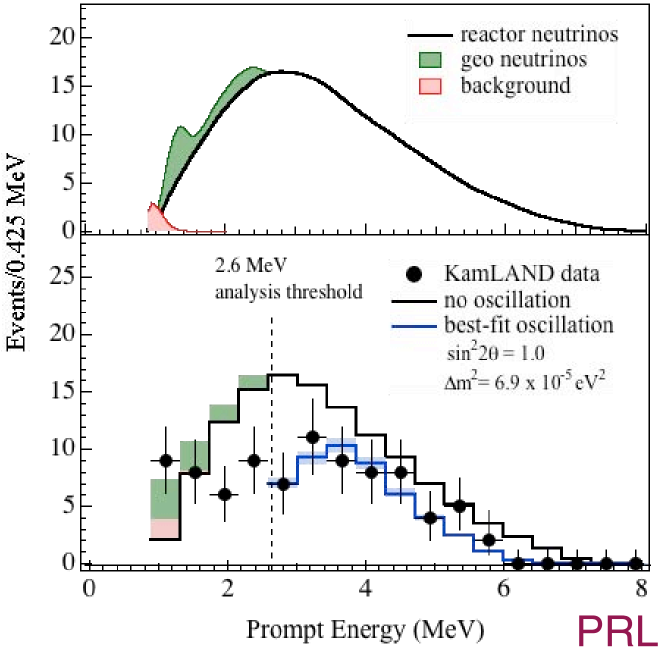
$|dR| < 1.6\ m$

$|dZ| > 1.2\ m$

First Direct Evidence for Reactor $\overline{\nu}_e$ Disappearance





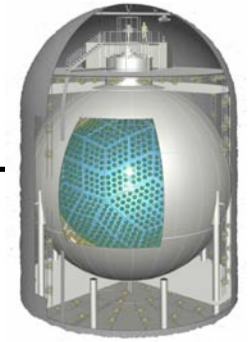


PRL 90:021802, 2003

Observed	**54 events**	syst err. 6.4%
	162 ton•yr, $E_{prompt} > 2.6\ MeV$	
No-Oscillation	**86.8 ± 5.6 events**	
Background	1 ± 1 events	
accidental	*0.0086 ± 0.0005*	
$^9Li/^8He$	*0.94 ± 0.85*	
fast neutron	*< 0.5*	

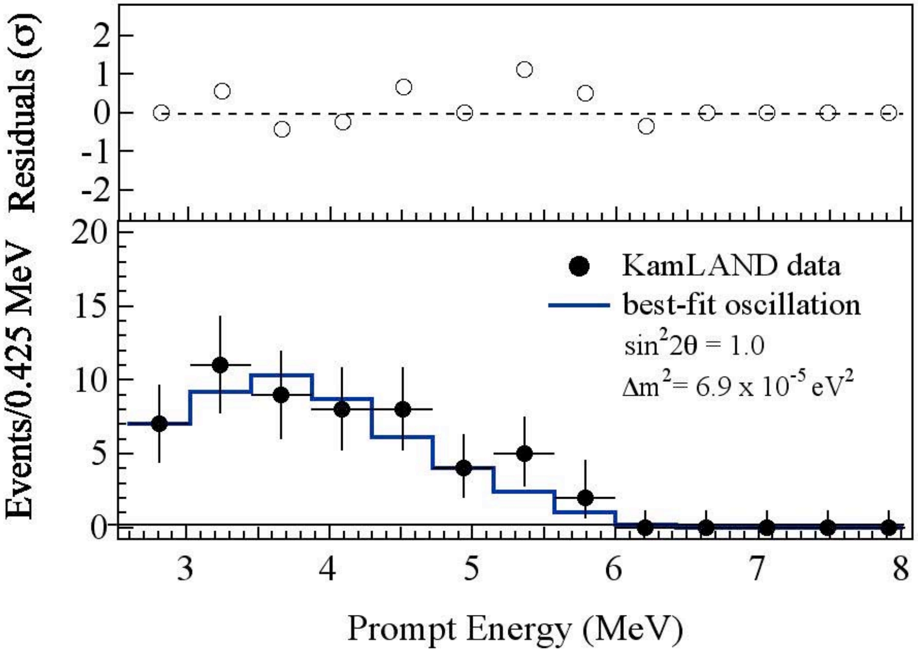
KamLAND provides evidence for neutrino oscillations together with solar experiments.

Is the KamLAND Neutrino Spectrum Distorted?

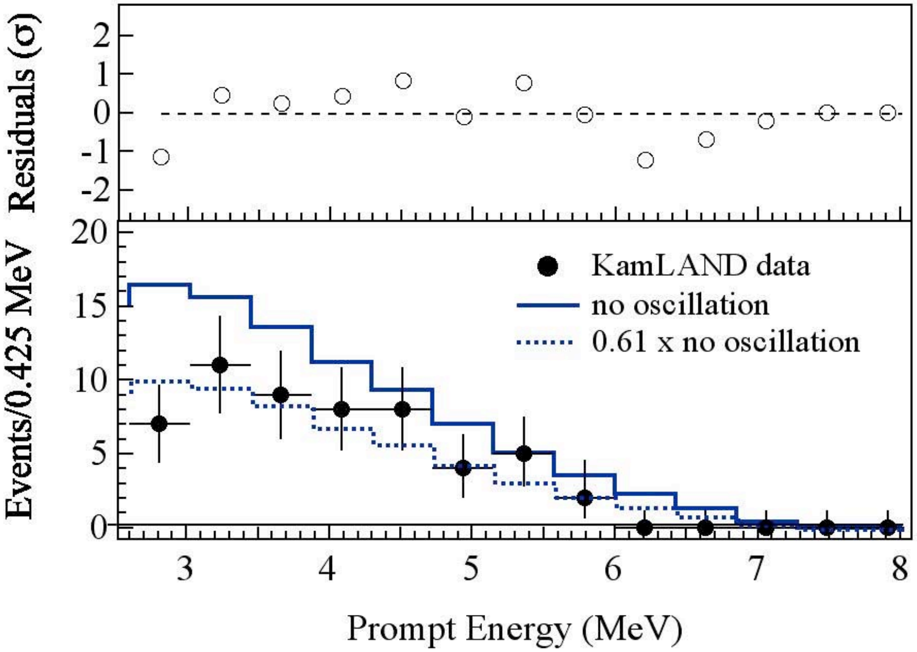


Search for a Unique Signature of Neutrino Oscillation

2-ν oscillation: best-fit



No oscillation, flux suppression



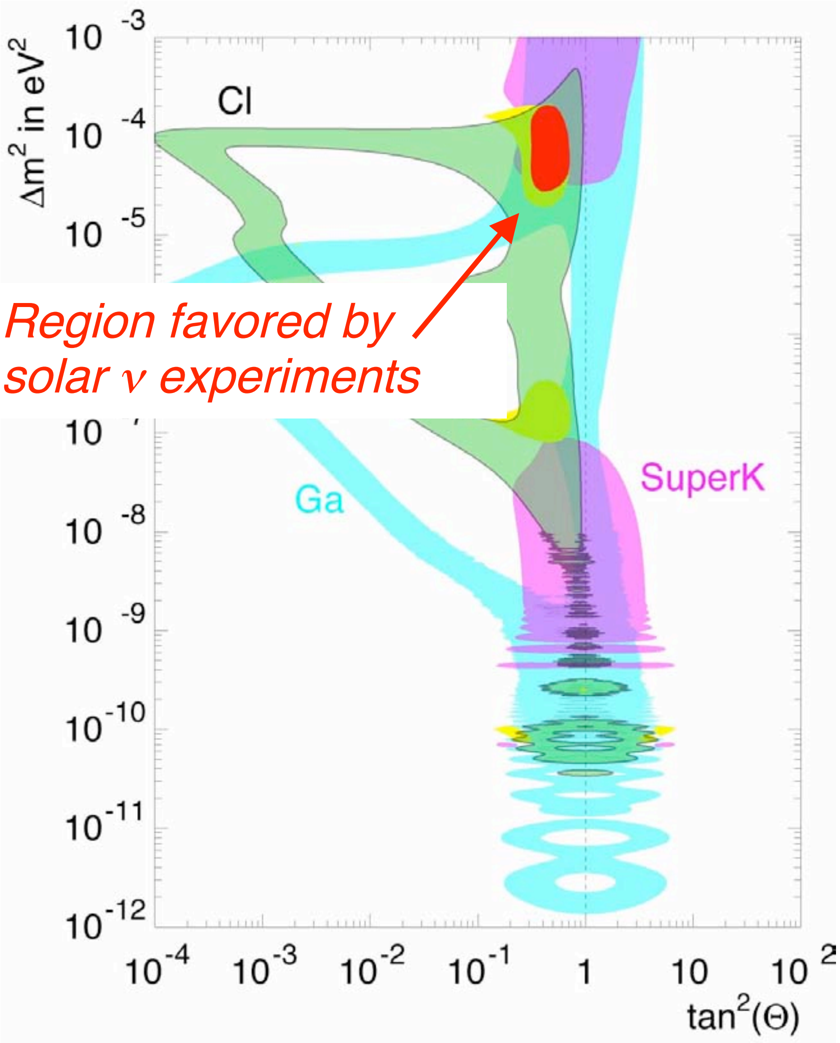
$\chi^2{}_{/\,8\ \mathrm{d.o.f}} = 0.31$

Data and best oscillation fit consistent at 93% C.L.

Data and best oscillation fit consistent at 53% C.L. as determined by Monte Carlo

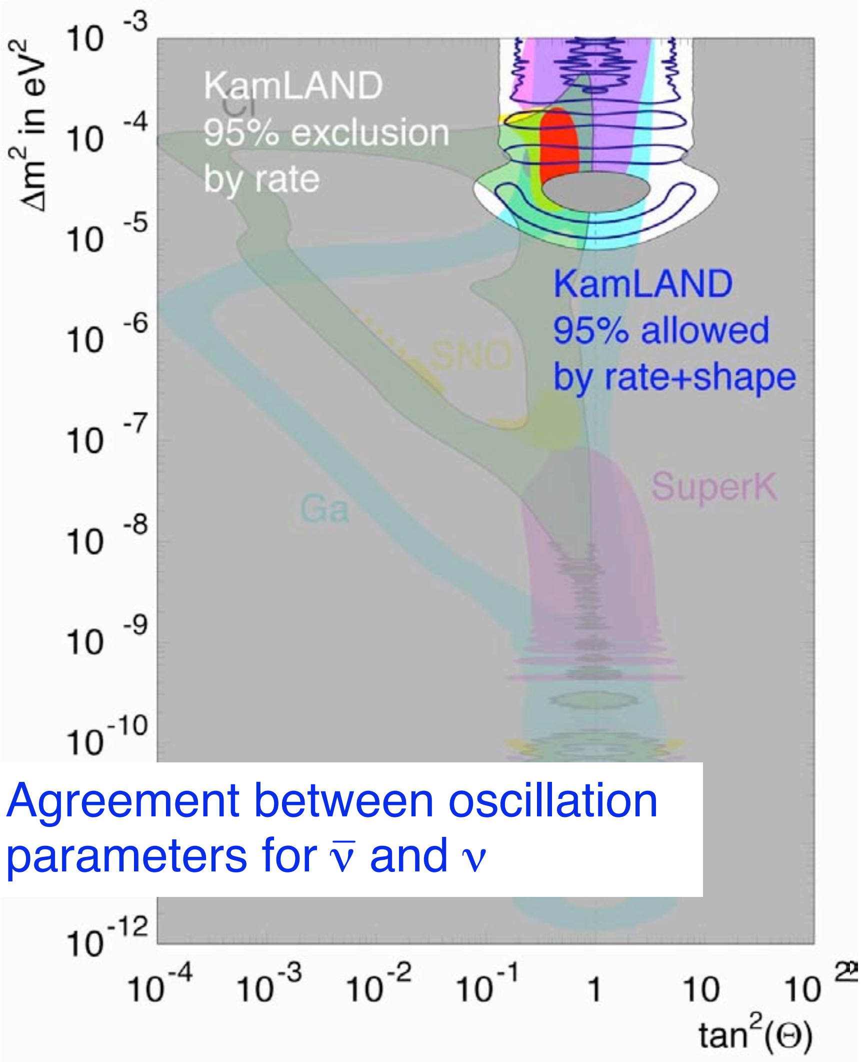
Oscillation Parameters *Before* and *After* KamLAND

Before KamLAND



Region favored by solar ν experiments

After KamLAND

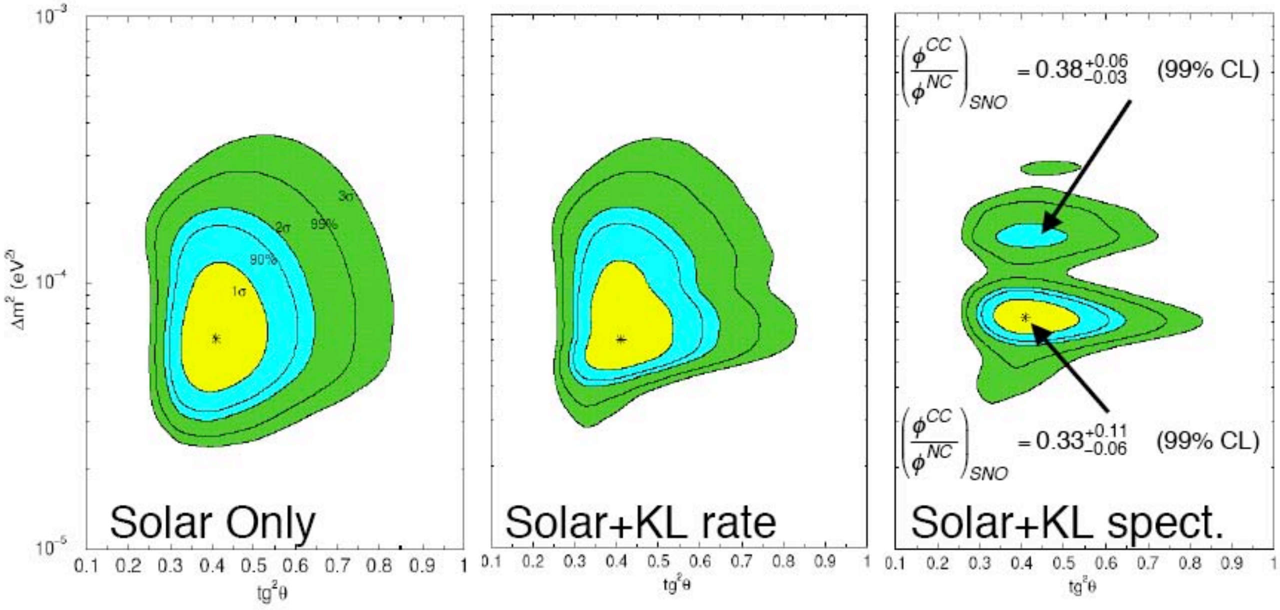


Agreement between oscillation parameters for $\bar{\nu}$ and ν

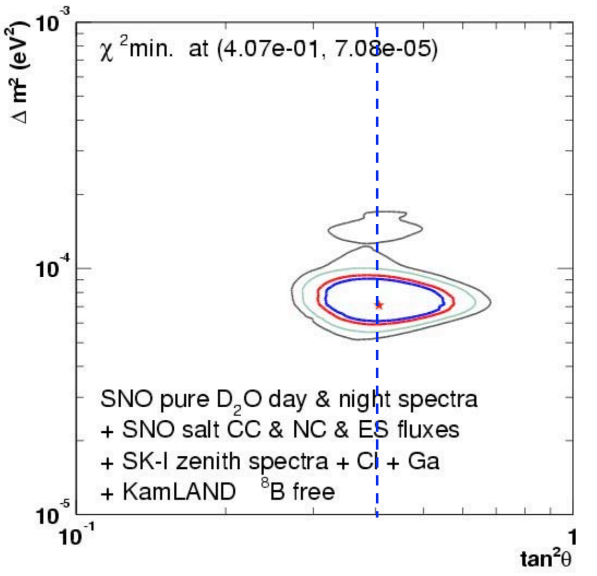
Determination of Oscillation Parameters Δm_{12}^2, θ_{12}

Before SNO-Salt

With SNO-Salt



de Holanda & Smirnov, hep-ph/0205241, hep-ph/0212270



Assume CPT

$|\Delta m_{\nu}^2 - \Delta m_{\bar{\nu}}^2| < 1.3 \times 10^{-3}$ eV^2 at 90% CL

→ LMA I only at > 99% CL

→ Maximal mixing ruled out (5.4σ)

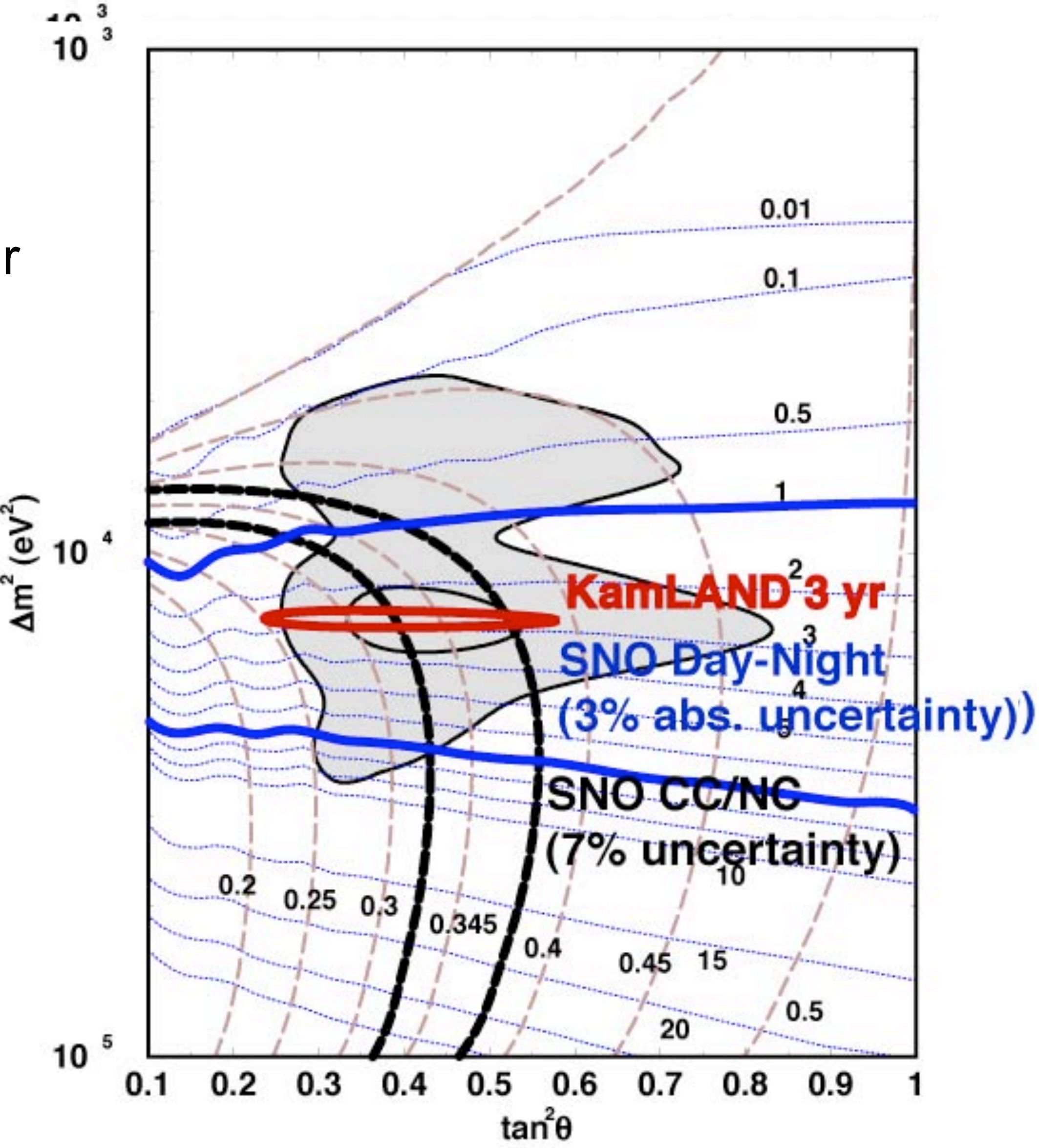
Possible Sterile Admixture?

KamLAND + SNO-Salt $\sin^2\eta_{sterile} < 0.09$

Defining θ_{12} and Δm_{12}^2 with SNO and KamLAND

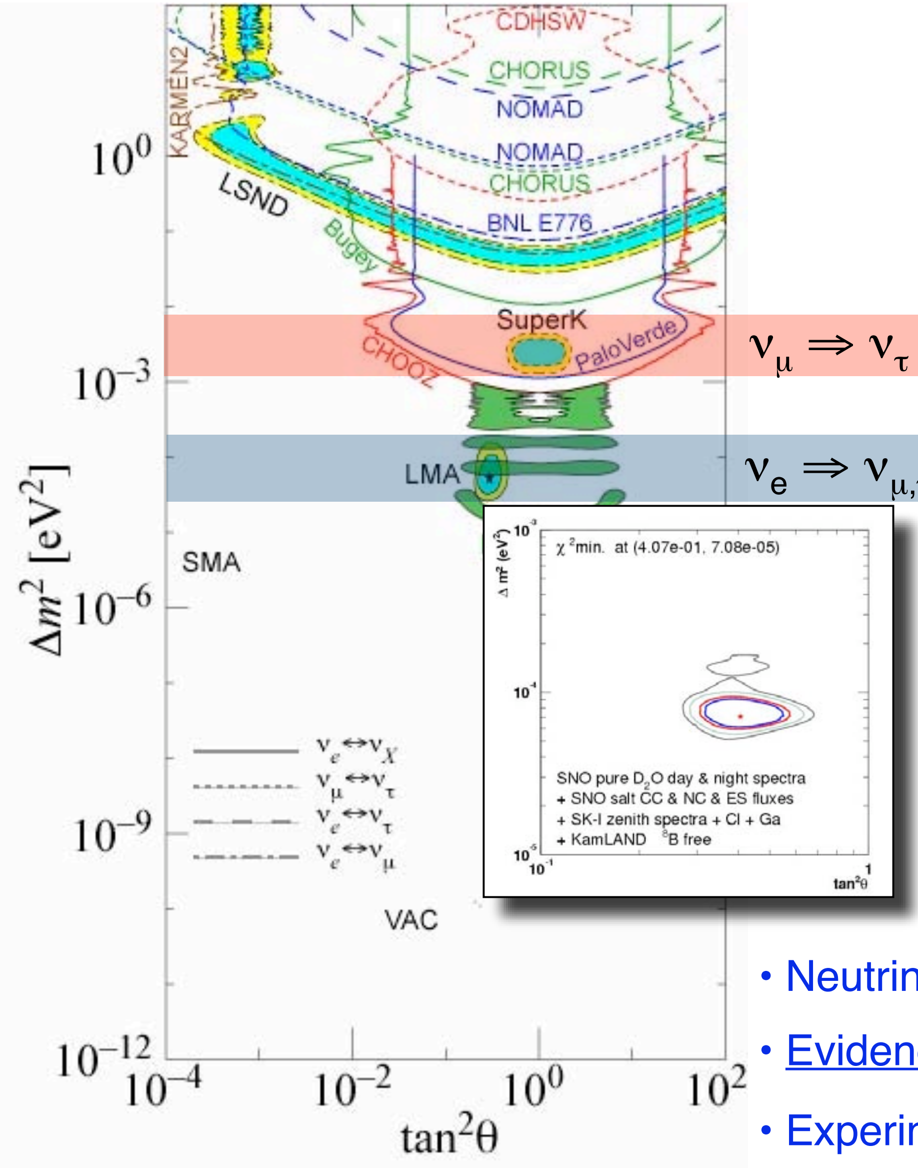
Is it all consistent?

Day/Night variation,
Spectrum from MSW Solar
versus
Reactor Oscillation …

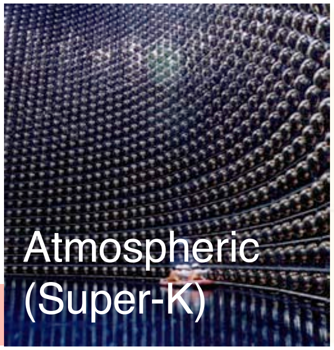


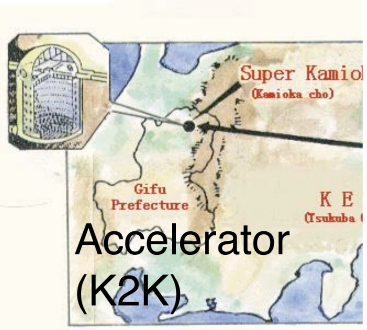
de Holanda et al., hep-ph/0212270,
Barger et al., hep-ph/0204253

Evidence for Mixing of Massive Neutrinos



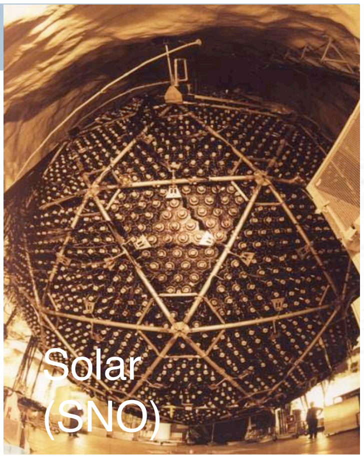
$\nu_\mu \Rightarrow \nu_\tau$

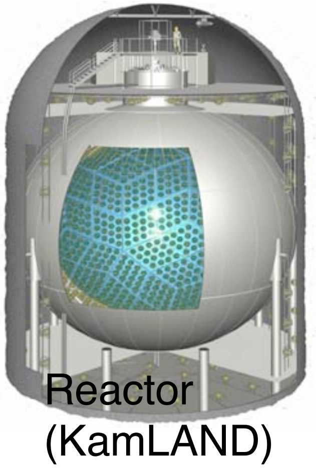

Atmospheric (Super-K)



Accelerator (K2K)

$\nu_e \Rightarrow \nu_{\mu,\tau}$


Solar (SNO)


Reactor (KamLAND)

- Neutrinos are not massless
- Evidence for neutrino flavor conversion $\nu_e \Leftrightarrow \nu_\mu \Leftrightarrow \nu_\tau$
- Experimental results show that *neutrinos oscillate*

Cosmological Implications

Experimental Results

Atmospheric neutrinos: $\Delta m_{23}^2 \approx 2.0 \times 10^{-3}\ \mathrm{eV}^2$

$\therefore$ one neutrino mass > 0.04 eV

SNO + KamLAND: $\Delta m_{12}^2 \approx 7.3 \times 10^{-5}\ \mathrm{eV}^2$

$\therefore$ one neutrino mass > 0.008 eV

Limits on “ν_e mass” give: $m(\nu_{1,2,3}) < 2.2$ eV

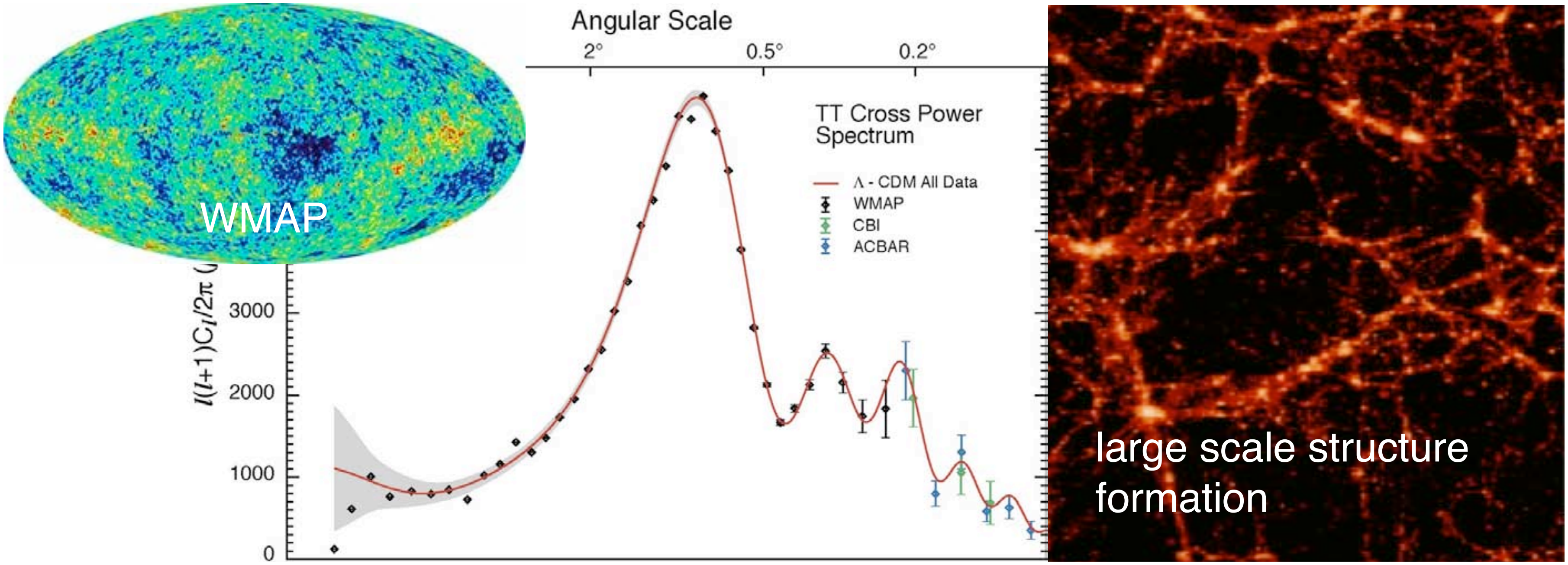
Implications

Σ of neutrino masses: $0.048 < m_1+m_2+m_3 < 6.6$ eV

Laboratory limit on n fraction of universe closure density: $0.001 < \Omega_\nu < 0.13$

Large-scale structure limit : $0.13 < \Omega_\nu < 0.02$

Cosmological Information on Neutrino Mass



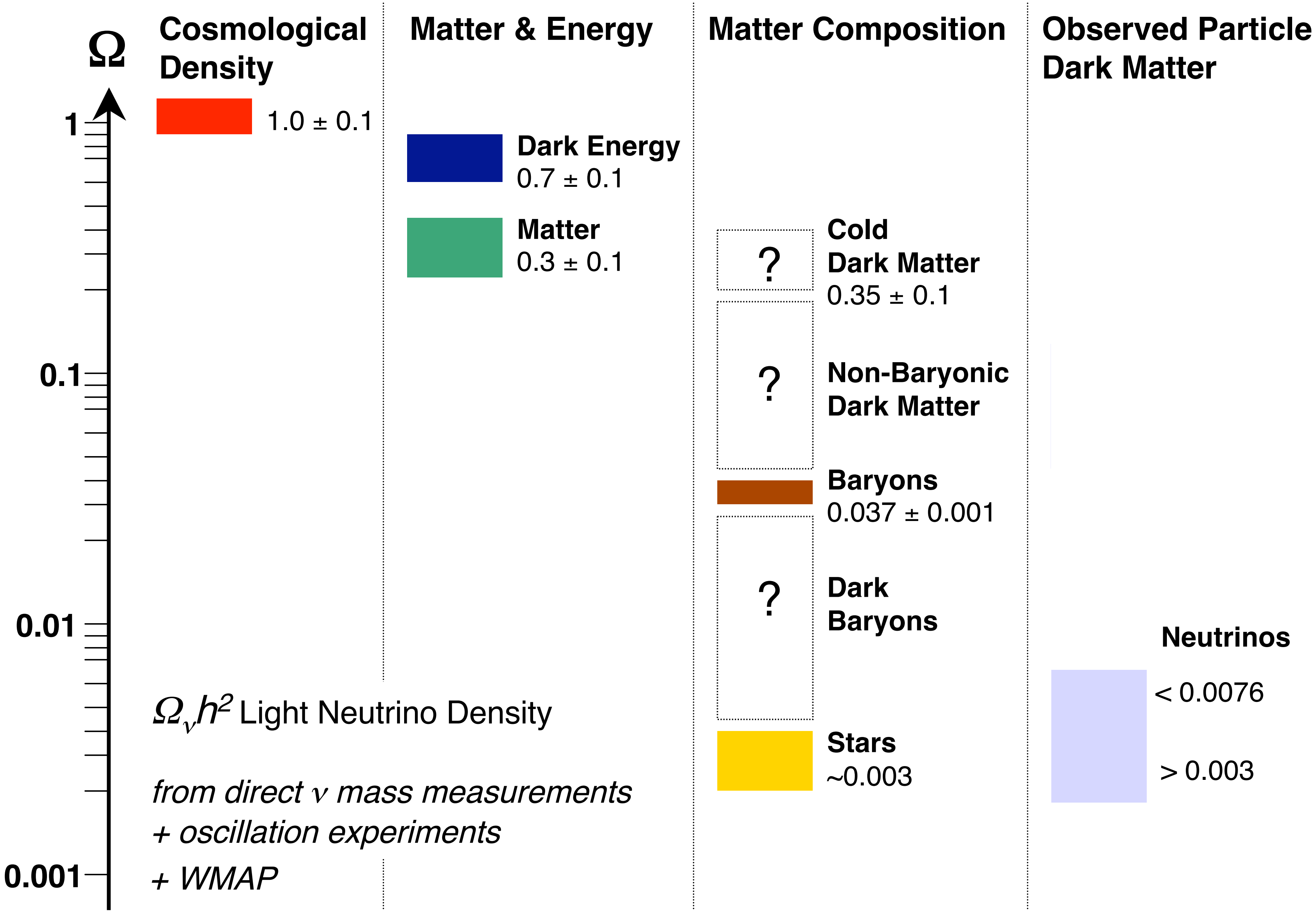
Neutrinos’ contribution to the Universe’s energy density $\Omega_\nu h^2 = \Sigma_i m_i / 95.3$ eV

Combining WMAP and large scale structure $\Omega_\nu h^2 < 0.0076$ eV (95% CL)

If $m_{\nu e} \sim m_{\nu\tau}$ (degenerate neutrino species) $m_\nu < 0.23$ eV

Cosmological neutrino mass limits probe Dirac and Majorana ν masses!

Mass limits comparable to $0\nu\beta\beta$ experiments.



Cosmological Density

1.0 ± 0.1

Matter & Energy

Dark Energy
0.7 ± 0.1

Matter
0.3 ± 0.1

Matter Composition

?
Cold Dark Matter
0.35 ± 0.1

?
Non-Baryonic Dark Matter

Baryons
0.037 ± 0.001

?
Dark Baryons

Stars
~0.003

Observed Particle Dark Matter

Neutrinos
< 0.0076
> 0.003

$\Omega_\nu h^2$ Light Neutrino Density

from direct ν mass measurements
+ oscillation experiments
+ WMAP

We have learned …

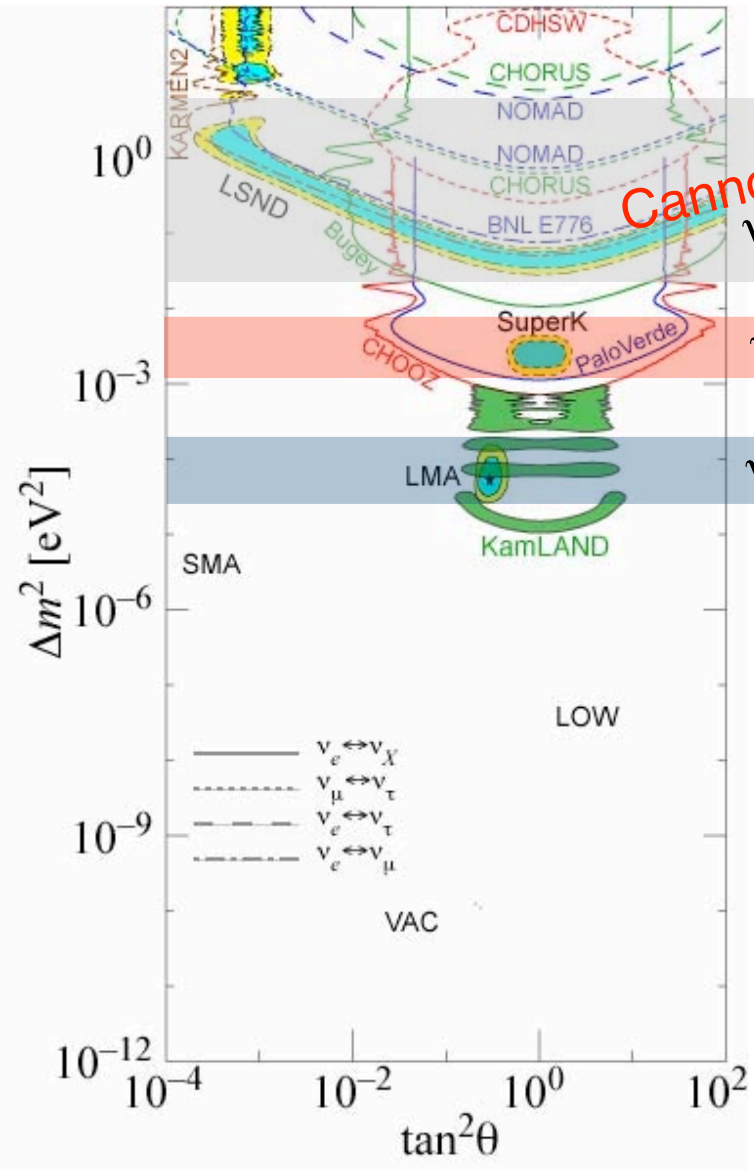
- ν transform flavor

- Atmospheric ν data explained extremely well by oscillations
  - primarily $\nu_\mu \rightarrow \nu_\tau$ conversion
  - mixing angle θ_{23} is very large, possibly maximal
  - $\Delta m^2 \sim 2 \times 10^{-3}$ eV^2

- Solar ν_e change primarily to other active ν's
  - if oscillations, mixing angle θ_{12} is large but not maximal and $\Delta m_{12} \sim 7 \times 10^{-5}$ eV^2 (LMA solution)
  - matter predicted to play a role in transformation
  - other modes for solar neutrino flavor transformation (sterile, RSFP, CPT …) can play only a subdominant role.

> *"…convincingly show that the flavor transitions of solar neutrinos are affected by Mikheyev-Smirnov-Wolfenstein (MSW) effects"*
>
> G.L. Fogli et. al, hep-ph/0309100

Other oscillations?

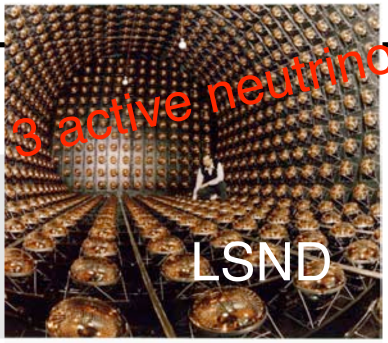


$\nu_\mu \Rightarrow \nu_e$?

$\nu_\mu \Rightarrow \nu_\tau$

$\nu_e \Rightarrow \nu_{\mu,\tau}$

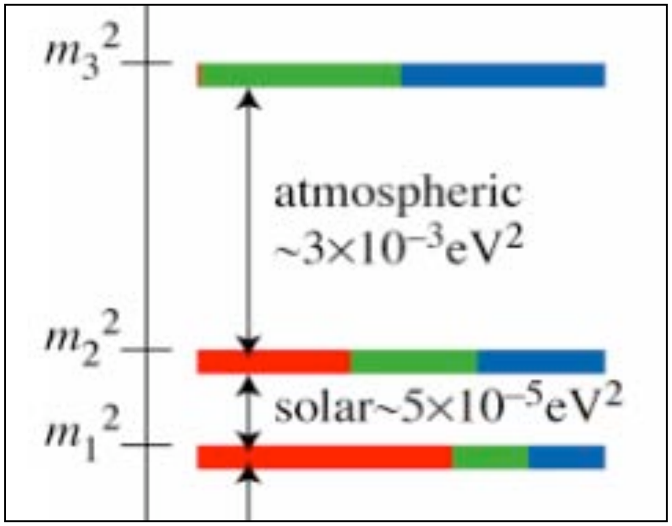
Cannot be explained by 3 active neutrinos!



L = 30m
E = ~40 MeV

Δm^2 = 0.3 to 3 eV^2
P_{OSC} = 0.3 %

Will be checked by MiniBoone at FNAL (2005?)



U_{MNSP}, θ_{13}, and $\cancel{CP}$

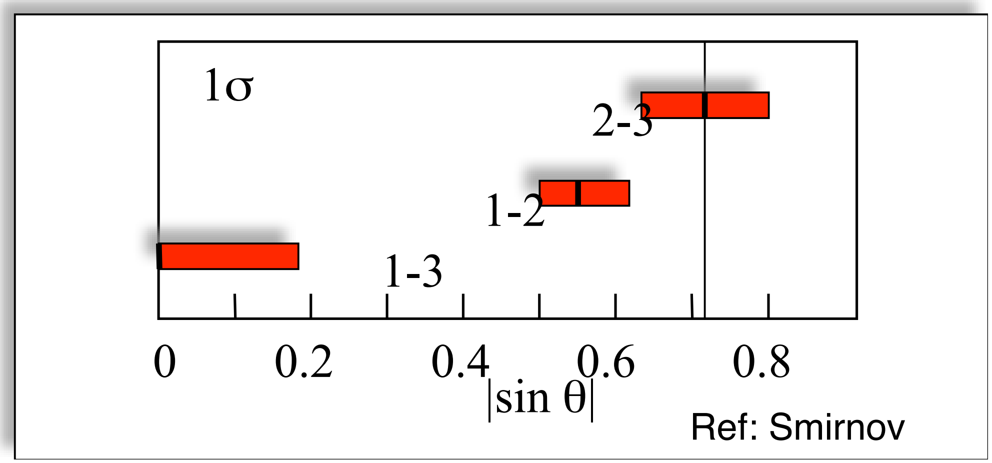
U_{MNSP} Neutrino Mixing Matrix

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

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \overbrace{\underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & \overset{?}{1} & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator}}}^{\textit{Dirac phase}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \overbrace{\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}}^{\textit{Majorana phases}}$$

$\theta_{23} = \sim 45°$ $\tan^2\theta_{13} < 0.03$ at 90% CL $\theta_{12} \sim 32°$

θ_{13} yet to be measured,
determines accessibility to CP phase

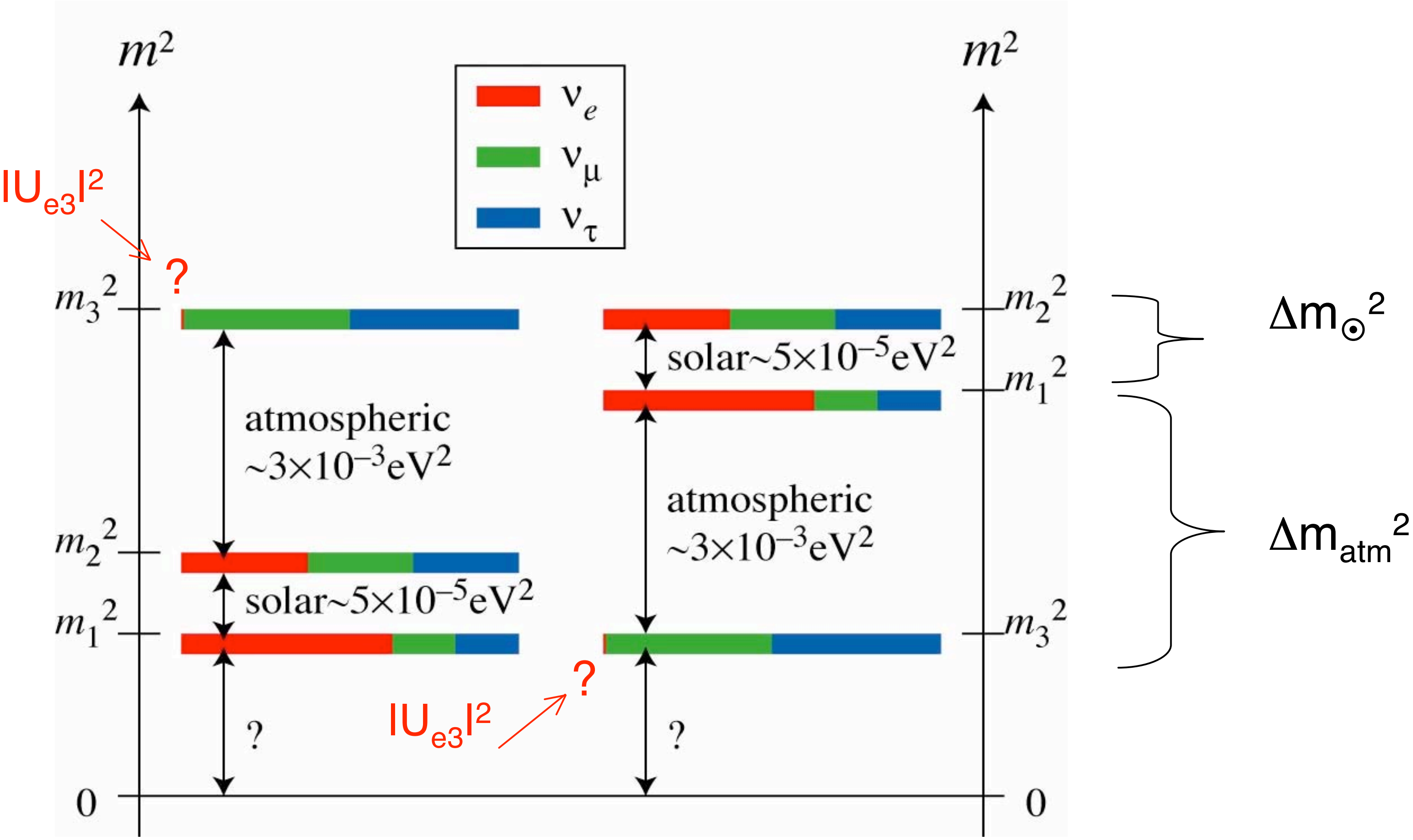


Ref: Smirnov

Neutrino Masses: What do we know?

Oscillation experiments

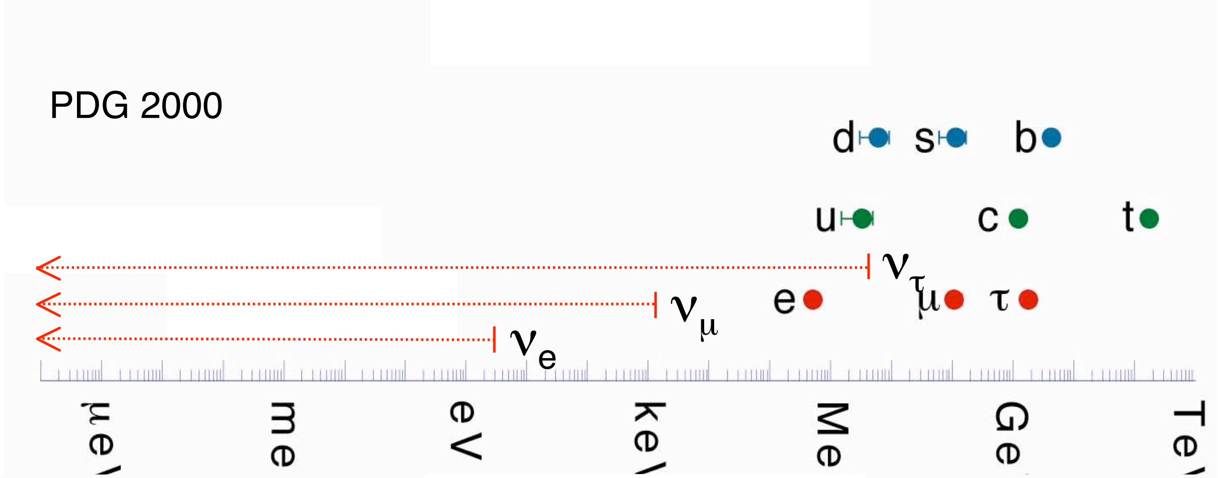
- indicate ν do have mass
- set the relative mass scale,
- set minimum for the absolute scale. $m_i > \sqrt{\Delta m^2_{atm}} \approx 50 meV$

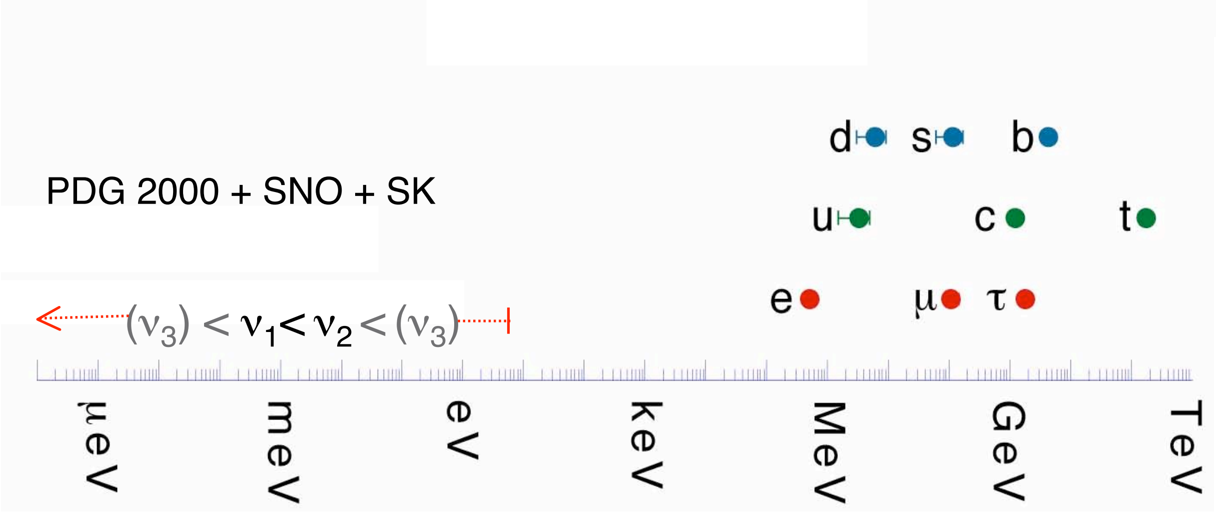


Constraining the Neutrino Mass

No fundamental reason why neutrinos must be massless.

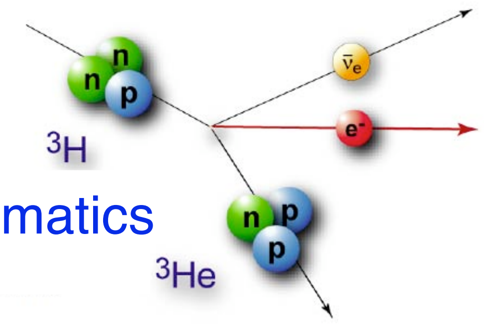
Fermion Masses





But why are they much lighter than other particles?

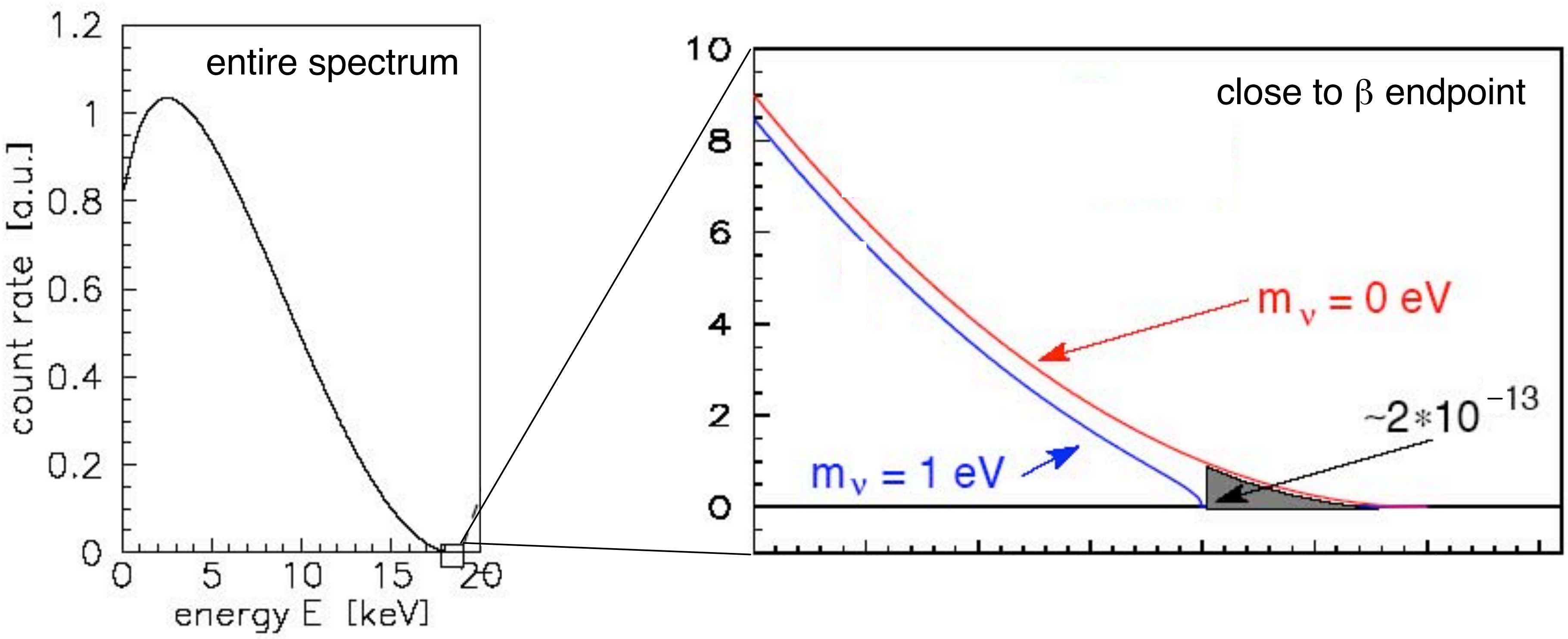
Direct Neutrino Mass Searches



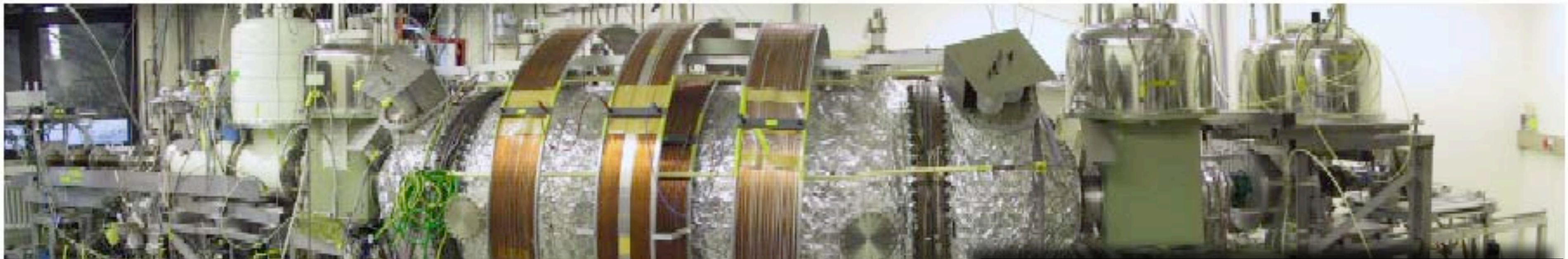
Model-Independent Neutrino Masses from ß-decay Kinematics

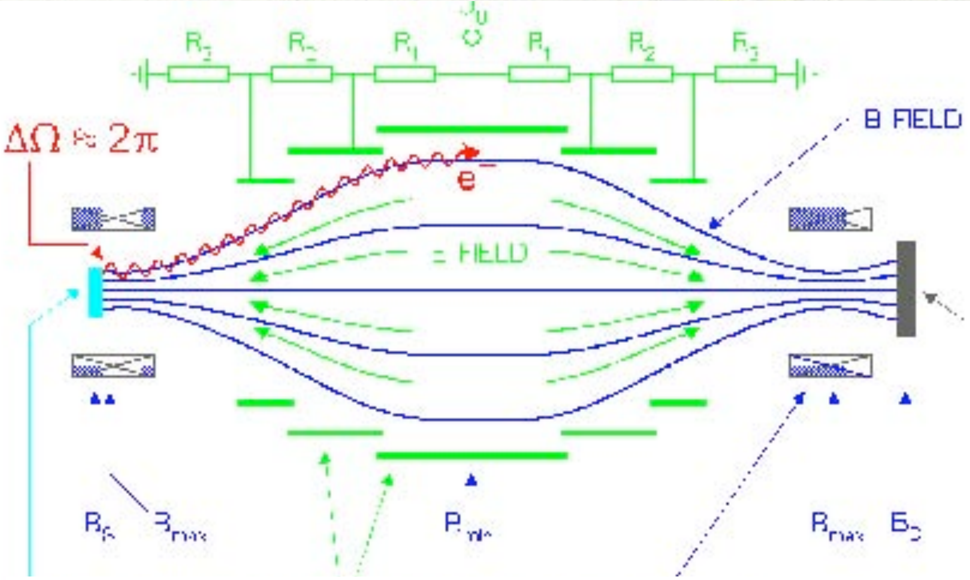
$$N(E_e) \propto p_e E_e \underbrace{(E_0 - E_e)}_{E_\nu} \sqrt{\underbrace{(E_0 - E_e)^2 - m_\nu{}^2 c^4}_{P_\nu}}$$

Search for a distortion in the shape of the β-decay spectrum in the end-point region

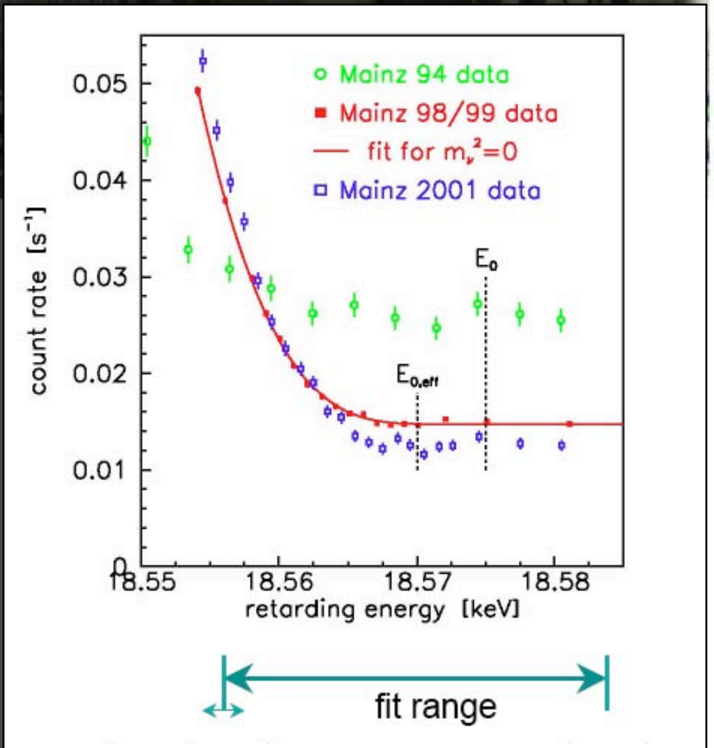


Mainz Neutrino Mass Experiment





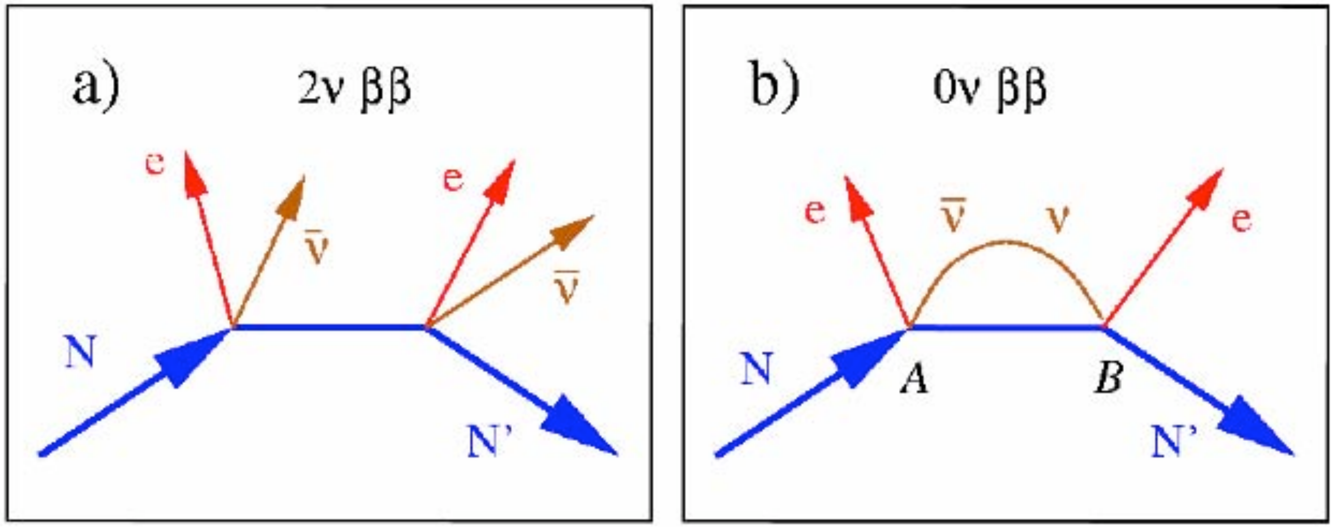
T_2 source electrodes solenoid detector



Current best limit $m_\nu < 2.2$ eV

Neutrinoless Double Beta Decay (0νββ)

The Next Frontier in Neutrino Physics



Gratta

2ν mode: conventional 2nd order process in nuclear physics

0ν mode: hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

$$\Gamma_{2\nu} = G_{2\nu} \mid M_{2\nu} \mid^2$$

$$\Gamma_{0\nu} = G_{0\nu} \mid M_{0\nu} \mid^2 \left\langle m_{\beta\beta} \right\rangle^2$$

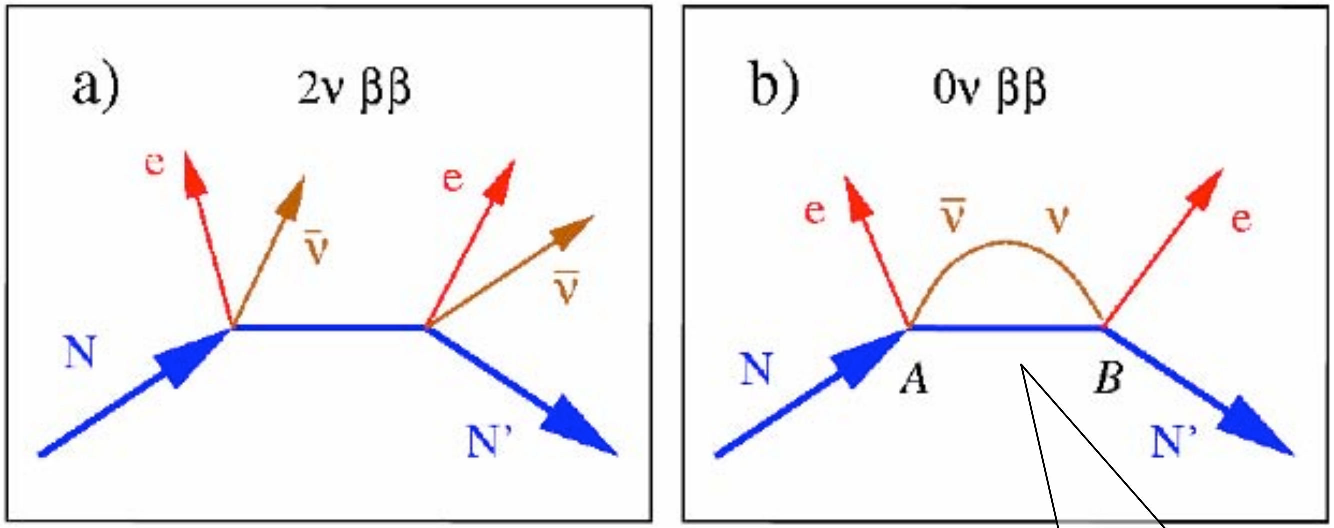
important physics

G are phase space factors

$G_{0n} \sim Q^5$

Neutrinoless Double Beta Decay (0νββ)

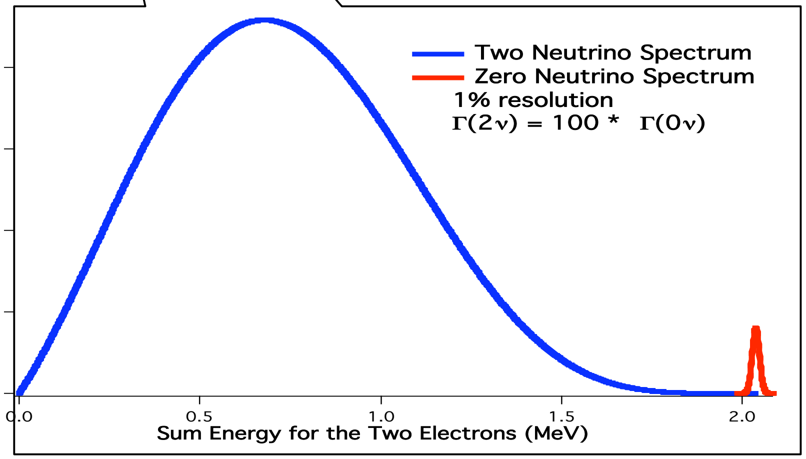
The Next Frontier in Neutrino Physics



Gratta

2ν mode: conventional 2nd order process in nuclear physics

0ν mode: hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$



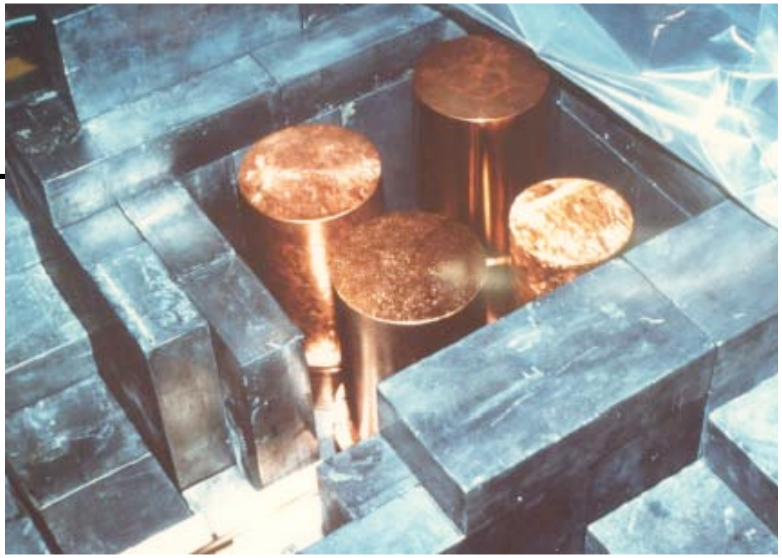
The only known practical approach to discriminate Majorana vs Dirac ν

Several Proposed 0νββ Experiments

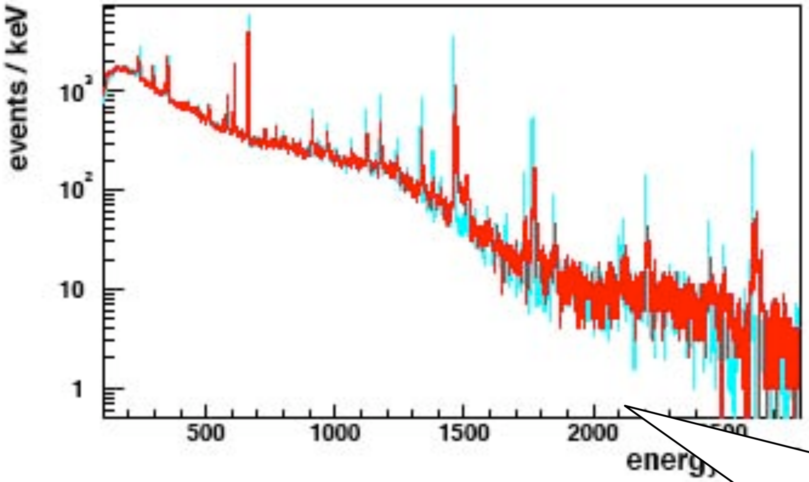
COBRA	Te-130	10 kg CdTe semiconductors
DCBA	Nd-150	20 kg Nd layers between tracking chambers
NEMO	Mo-100, Various	10 kg of bb isotopes (7 kg of Mo)
CAMEO	Cd-114	1 t $CdWO_4$ crystals
CANDLES	Ca-48	Several tons CaF_2 crystals in liquid scint.
CUORE	Te-130	750 kg TeO_2 bolometers
EXO	Xe-136	1 ton Xe TPC (gas or liquid)
GEM	Ge-76	1 ton Ge diodes in liquid nitrogen
GENIUS	Ge-76	1 ton Ge diodes in liquid nitrogen
GSO	Gd-160	2 t Gd_2SiO_5:Ce crystal scint. in liquid scint.
Majorana	Ge-76	500 kg Ge diodes
MOON	Mo-100	Mo sheets between plastic scint., or liq. scint.
Xe	Xe-136	1.56 t of Xe in liq. Scint.
XMASS	Xe-136	10 t of liquid Xe

The $\langle m_{\beta\beta} \rangle$ limits depend on background assumptions and matrix elements which vary from proposal to proposal.

A Recent Claim for $0\nu\beta\beta$ in ^{76}Ge



5 detectors of overall 10.96 kg enriched to 86-88% in the $\beta\beta$-emitter ^{76}Ge



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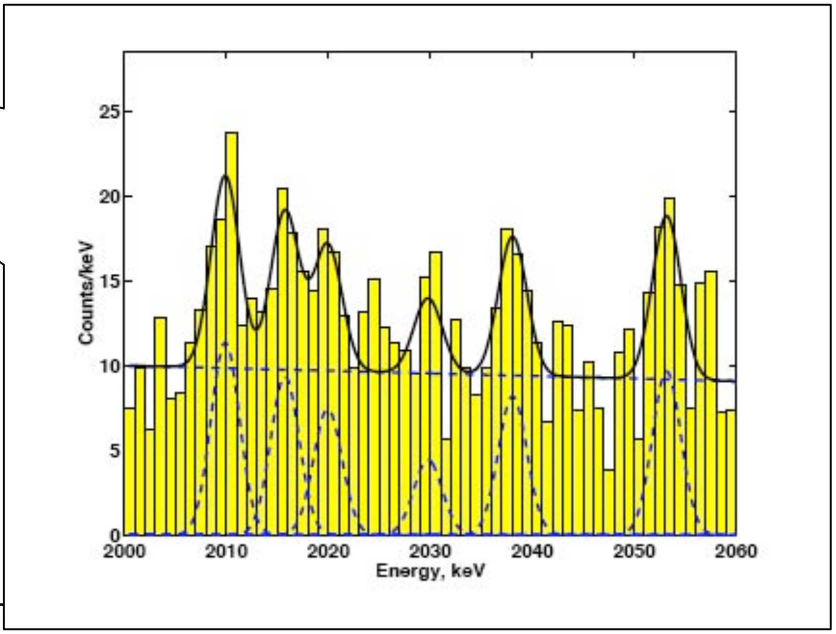

T = (0.69 - 4.18) x 10^{25} years (3 σ)

Majorana ν Mass

m_ν= (0.24 - 0.58) eV (3 σ)

$m_{\nu\ \text{best}}$ = 0.44 eV

Massive Neutrinos? Yes!

ν transform flavor

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

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

Data explained well by oscillation, other solutions disfavored.

What else?

- What are the absolute masses?
- What is the level ordering of 2,3 (or 1,3)?
- Are ν's Dirac or Majorana particles?

→ Direct mass measurements and $0\nu\beta\beta$

- What are the values of Δm^2, U_{ij}?

→ Reactor and accelerator experiments

- How many mass states? Are there sterile ν?

→ MiniBoone

A very exciting time for neutrino physics

XXIst International Conference on Neutrino Physics and Astrophysics

NEUTRINO 2004

14-19 June

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More to come …