Neutrino Oscillations

Heidi Schellman

June 6, 2000

Lots of help from Janet Conrad

Standard Model of Elementary Particles

Charge
mass,MeV

	3 Generations of Fermions			Force Carriers	
Quarks	2/3 u ~5	2/3 c ~1350	2/3 t 175000	0 g 0	Strong Interactions
	−1/3 d ~9	−1/3 s ~175	−1/3 b ~4500	0 γ 0	Electro-magnetism
Leptons	ν_e 0?	ν_μ 0?	ν_τ 0?	0 Z^0 91187	Weak Interactions
	e 0.511	μ 105.66	τ 1777.2	±1 $W^\pm$ 81400	

Masses are in MeV

July 1997

Fermions in the Weak Interactions

Leptons

$$\psi_L = \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix} = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

$$\psi_R = \overline{\ell} = e^+, \mu^+, \tau^+$$

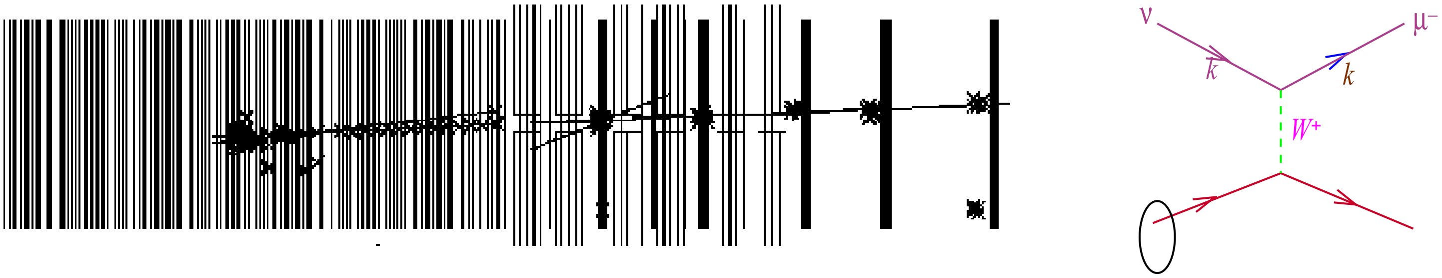
Quarks

$$\psi_L = \begin{pmatrix} \mathrm{u}_i \\ \mathrm{d}'_i \end{pmatrix} = \begin{pmatrix} \mathrm{u} \\ \mathrm{d}' \end{pmatrix}, \begin{pmatrix} \mathrm{c} \\ \mathrm{s}' \end{pmatrix}, \begin{pmatrix} \mathrm{t} \\ \mathrm{b}' \end{pmatrix}$$

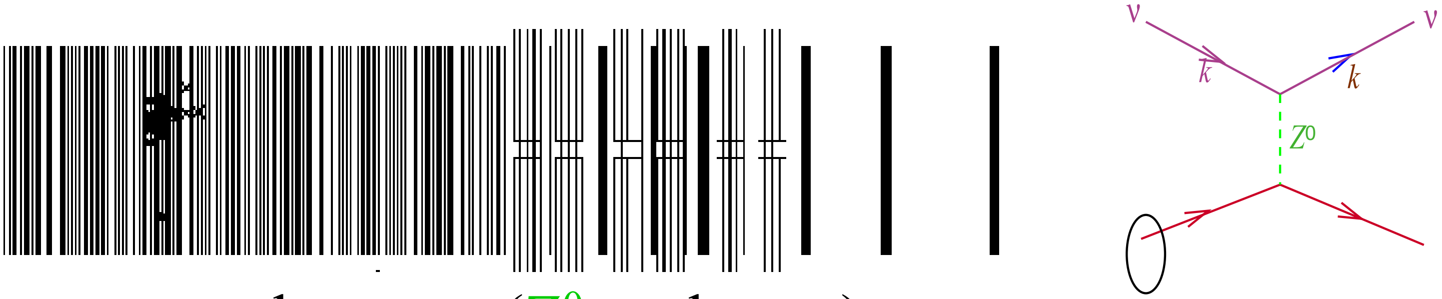
$$\psi_R = \overline{\mathrm{q}}_i = \overline{\mathrm{u}}, \overline{\mathrm{c}}, \overline{\mathrm{d}}$$

No weak interactions for right handed ν or Left handed anti-ν

Two types of neutrino interactions,
One transforms neutrino to lepton
Other doesn’t



charged current (W exchange)



neutral current (Z^0 exchange)

Weak Interactions

Mass Eigenstates

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

Weak 'quarks' are not mass eigenstates

$$\mathbf{V} = \begin{pmatrix} 0.9745 - 0.9760 & 0.217 - 0.224 & 0.0018 - 0.0045 \\ 0.217 - 0.224 & 0.9737 - 0.9753 & 0.036 - 0.042 \\ 0.004 - 0.013 & 0.035 - 0.042 & 0.9991 - 0.9994 \end{pmatrix}$$

The quark sector shows significant mixing between generations – what about leptons?

Mixing in the Lepton Sector

- If neutrinos are massless, there may be mixing but it is durned hard to see.

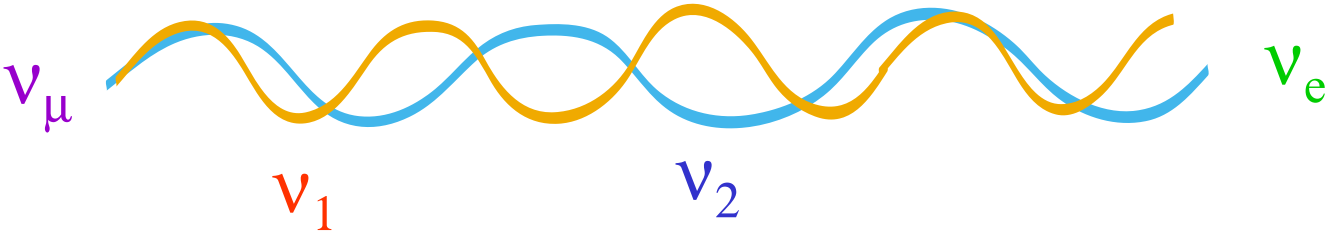
- If neutrinos have different masses then, in principle, their weak flavor should evolve as they travel through space.

Two flavor mixing

- Assume that the weak eigenstates ν_e and ν_μ are mixtures of the mass eigenstates ν_1 and ν_2

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

- Then the time evolution of a ν_μ is



$$|\nu(0)>=|\nu_\mu>=-\sin\theta|\nu_1>+\cos\theta|\nu_2>$$

$$|\nu(t)>=-\sin\theta e^{-iE_1t}|\nu_1>+\cos\theta e^{-iE_2t}|\nu_2>$$

- The probability of seeing an electron neutrino at time t is:

$$P(t) = | < \nu_e | \nu(t) > |^2 = \frac{1}{2} \sin^2 2\theta [1 - \cos(E_2 - E_1)t]$$

- Because the two mass states have different wavelengths.
- If E >> m then:

$$E \sim p + \frac{m^2}{2p} \qquad \frac{t}{p} \simeq \frac{L}{E}$$

- So:

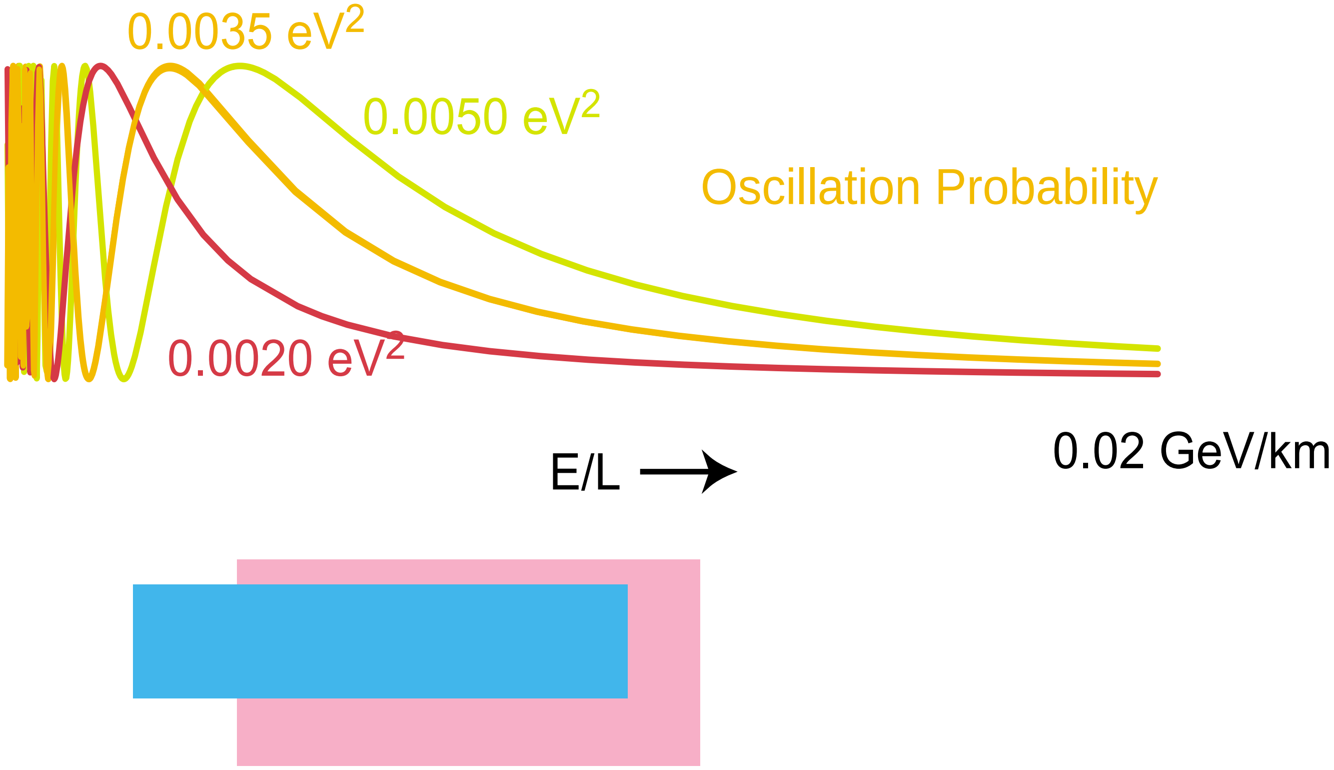
$$P(L) = | < \nu_e | \nu(t) > |^2 = \sin^2 2\theta \sin^2 [\frac{(m_2^2 - m_1^2)L}{4E}]$$

$$P(L) = | < \nu_e | \nu(t) > |^2 = \sin^2 2\theta \sin^2 [\frac{1.27 \Delta m^2 L}{4E}]$$

- Where L is in km, E is in GeV, m is in eV

Experiments can be described by their E/L coverage

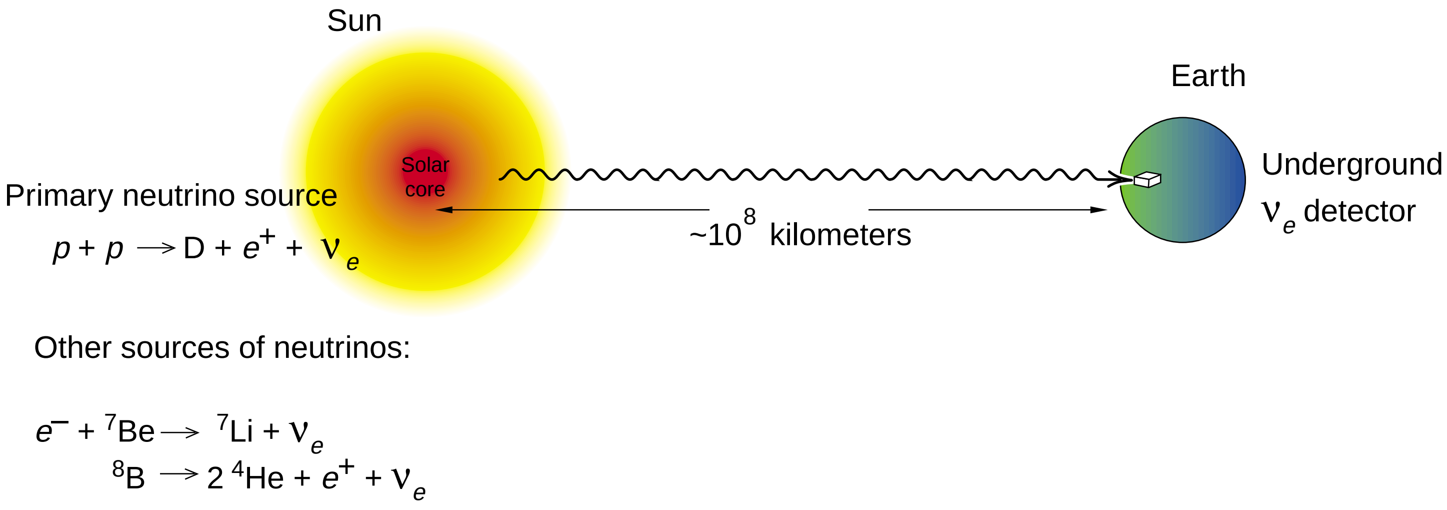
- $P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2 2\theta \, \sin^2[1.27 \Delta m^2 \, L/E]$
- m in eV, L in km, E in GeV

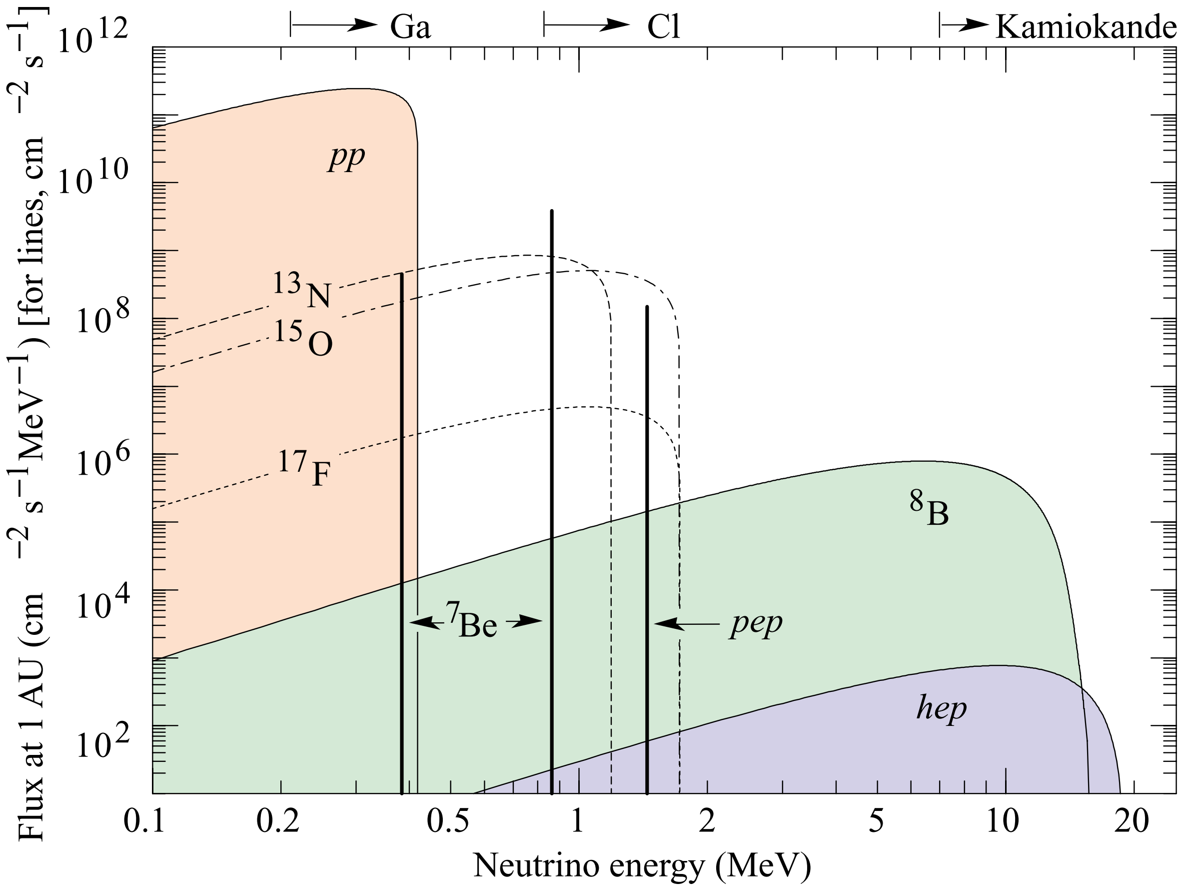


If E/L << Δm^2, $P(\nu_\alpha \rightarrow \nu_\beta) \sim ½ \sin^2 2\theta$

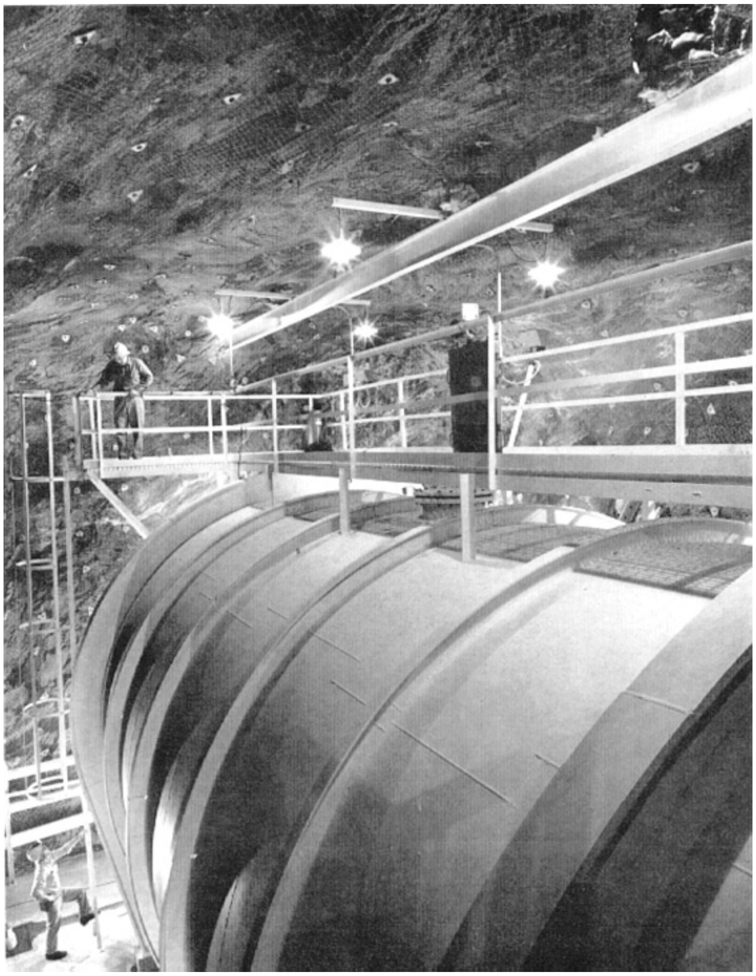
If E/L >>Δm^2, $P(\nu_\alpha \rightarrow \nu_\beta) \sim 0$

If E/L ~ Δm^2, can measure both Δm^2 and $\sin^2 2\theta$


Sun
Solar core
Primary neutrino source
p + p → D + e+ + νe
~10^8 kilometers
Earth
Underground
νe detector
Other sources of neutrinos:
e− + 7Be → 7Li + νe
8B → 2 4He + e+ + νe


Ga
Cl
Kamiokande
pp
13N
15O
17F
8B
7Be
pep
hep
10^12
10^10
10^8
10^6
10^4
10^2
0.1
0.2
0.5
1
2
5
10
20
Neutrino energy (MeV)
Flux at 1 AU (cm−2 s−1 MeV−1) [for lines, cm−2 s−1]

Solar neutrino detectors



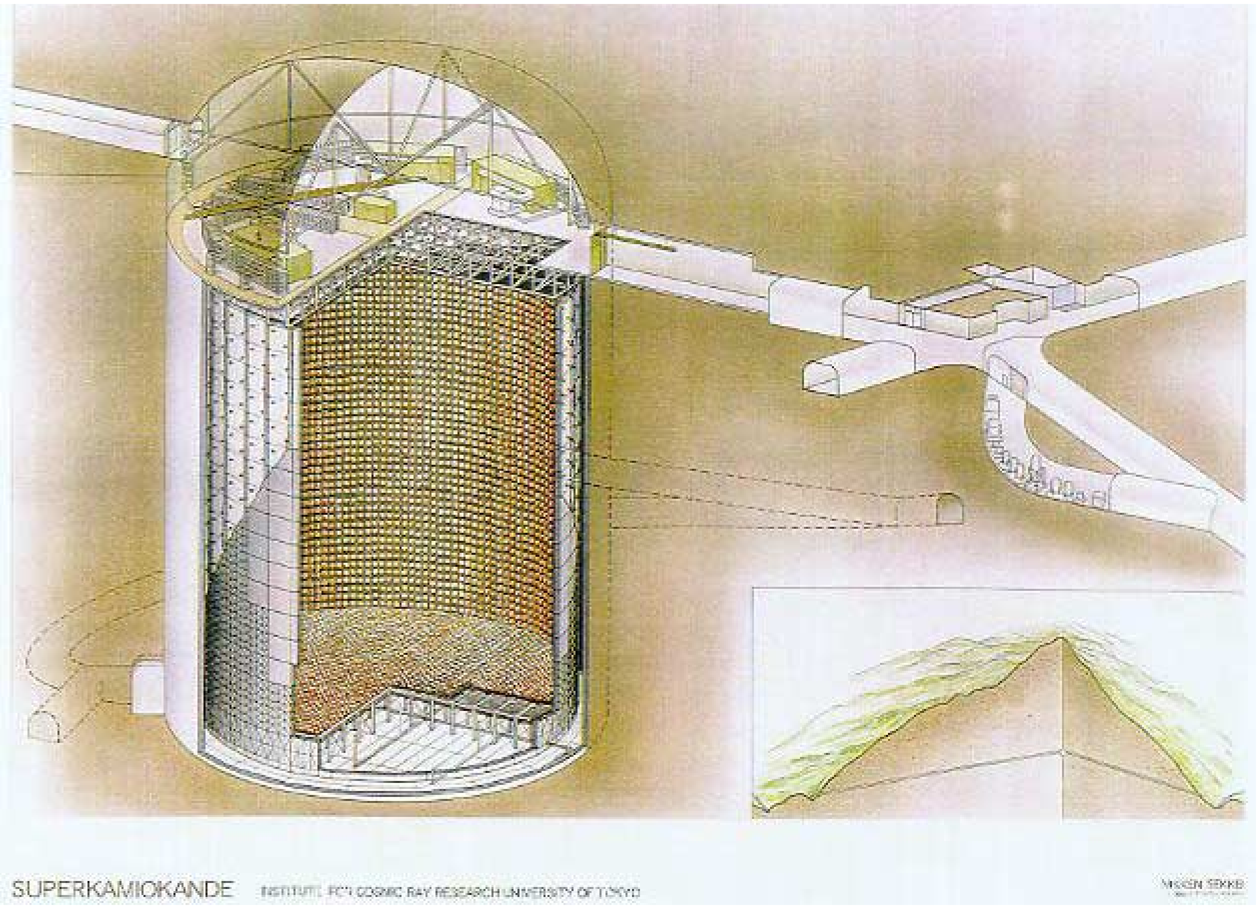
$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

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

Homestake, Sage, Gallex extract Argon and Ge from large samples of Cl and Ga

SuperKamiokande

50kTons Water, 11,146 50-cm γ-tubes



Cerenkov Detectors

From side Ring

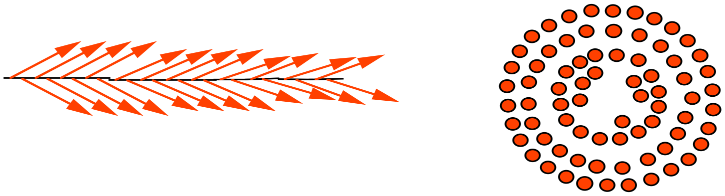
short track,
no multiple
scattering

Sharp
Ring

electrons:
short track,
mult. scat.,
brems.

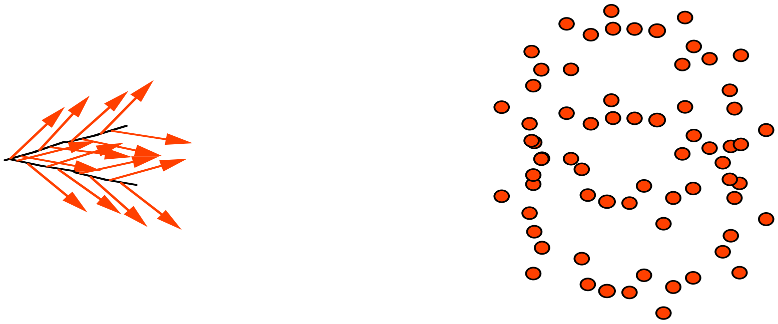
Fuzzy
Ring

muons:
long track,
slows down

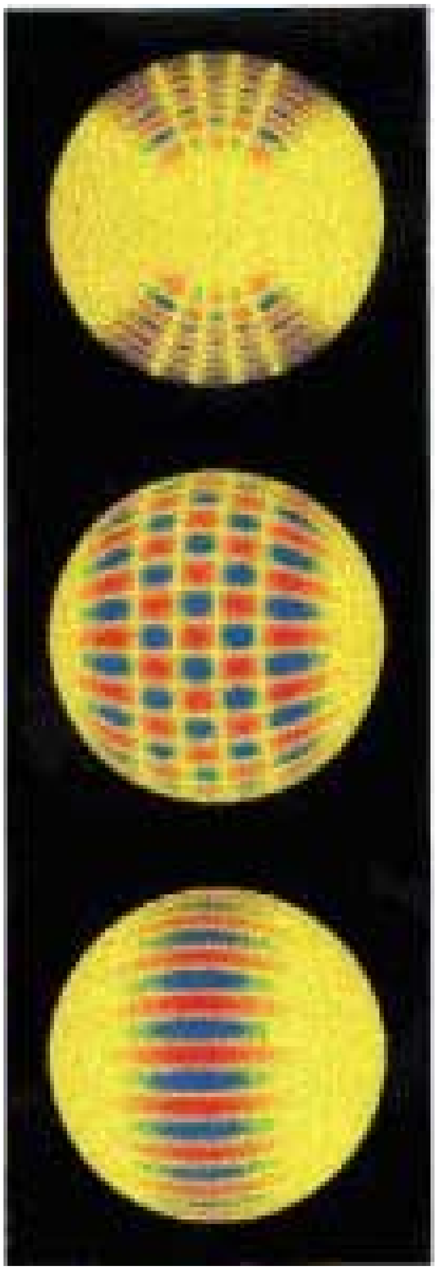


Sharp Outer
Ring with
Fuzzy
Inner
Region

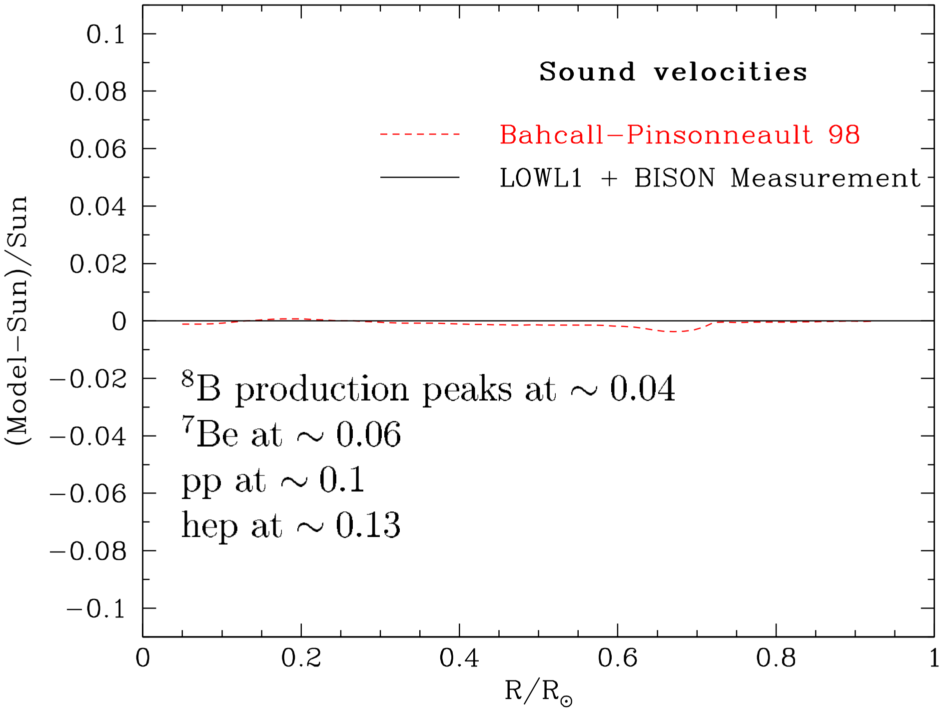
neutral pions:
2 electron-like
tracks



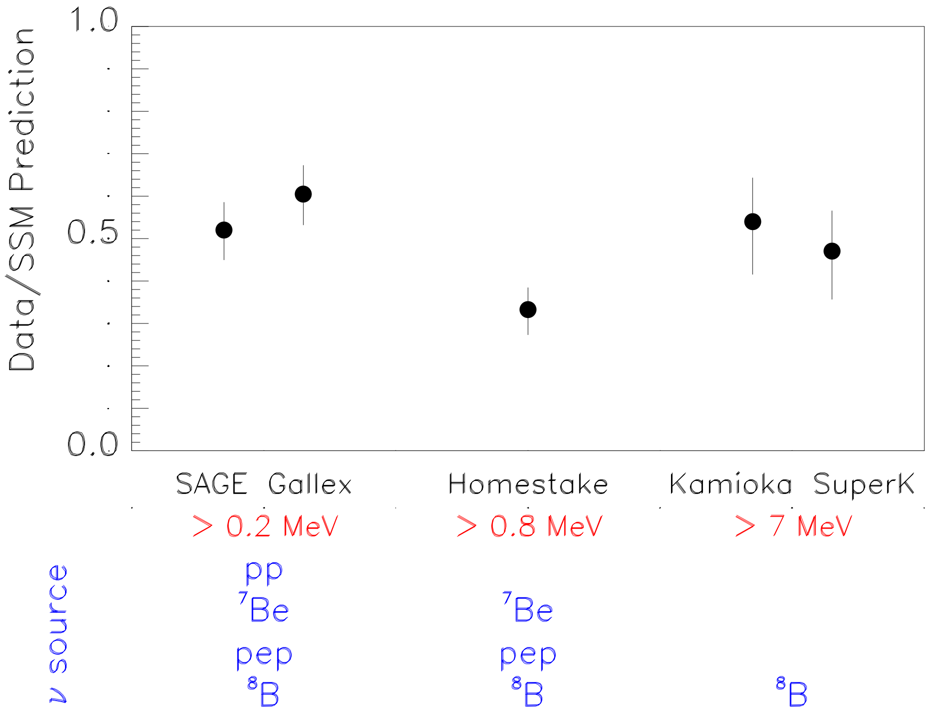
Two
Fuzzy
Rings



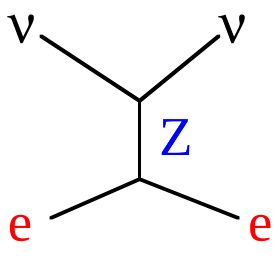
- Solar models
  - Use integro-differential equations to extrapolate from surface to core
  - Need to know composition of sun
  - Use nuclear cross sections for processes at the core. Some go as T^{10}
  - Need to know about diffusive, convective zones
  - Make predictions for ratios of different processes
- Can now be checked by helio-seismology!



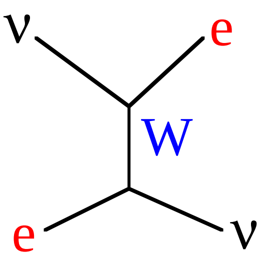
Results of solar neutrino experiments



All energy ranges are consistent with lower numbers of neutrinos. This is hard to explain with a multi-process solar model but easy to explain with a loss of neutrinos between sun and earth.

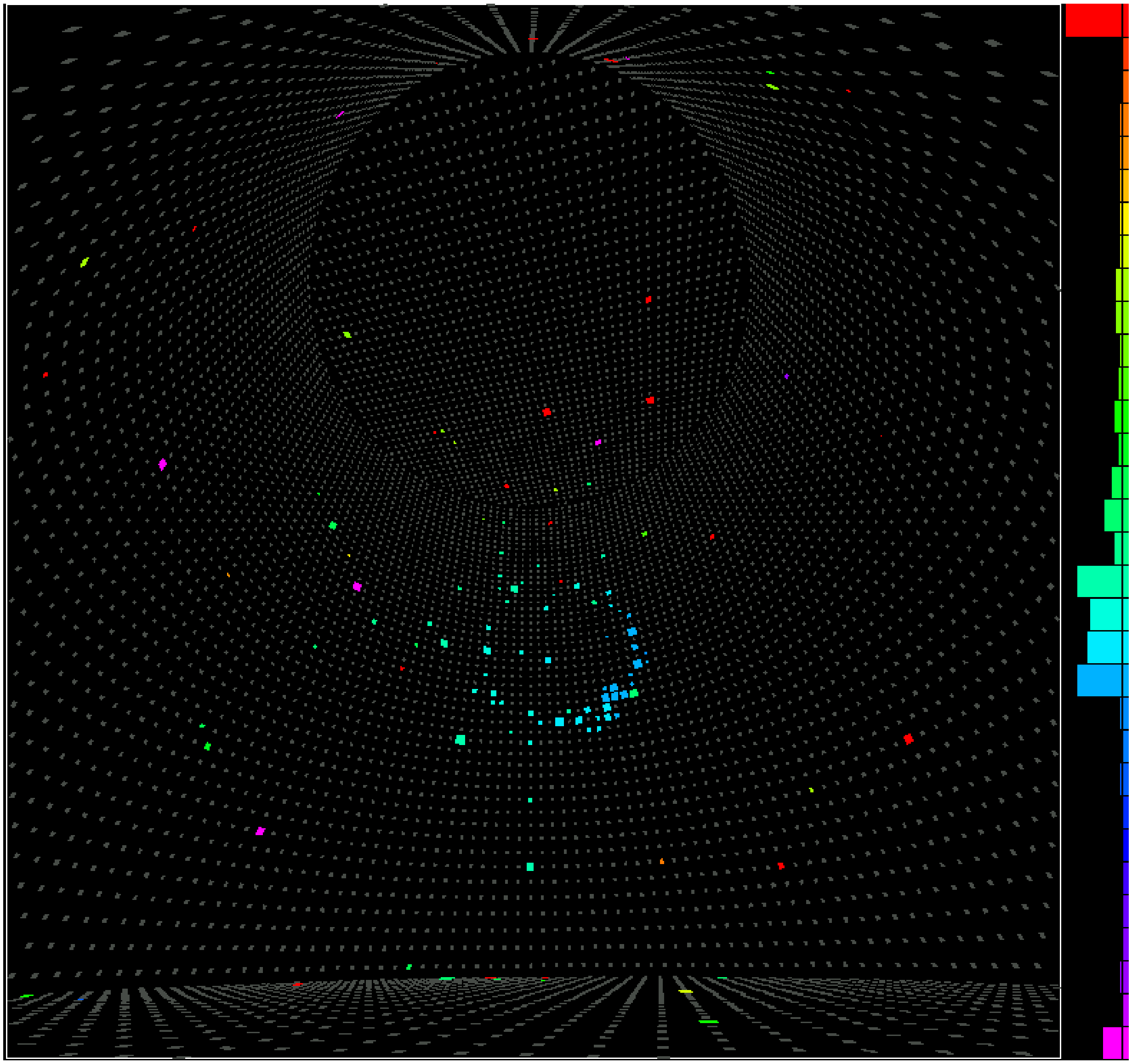


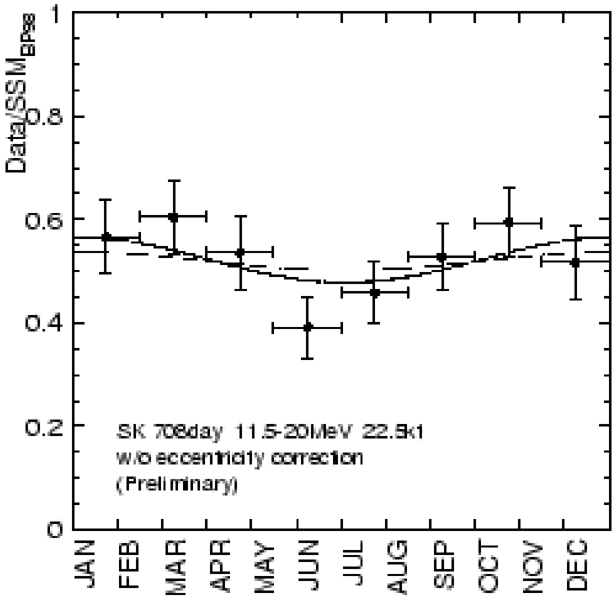
ν_e, ν_μ, ν_τ



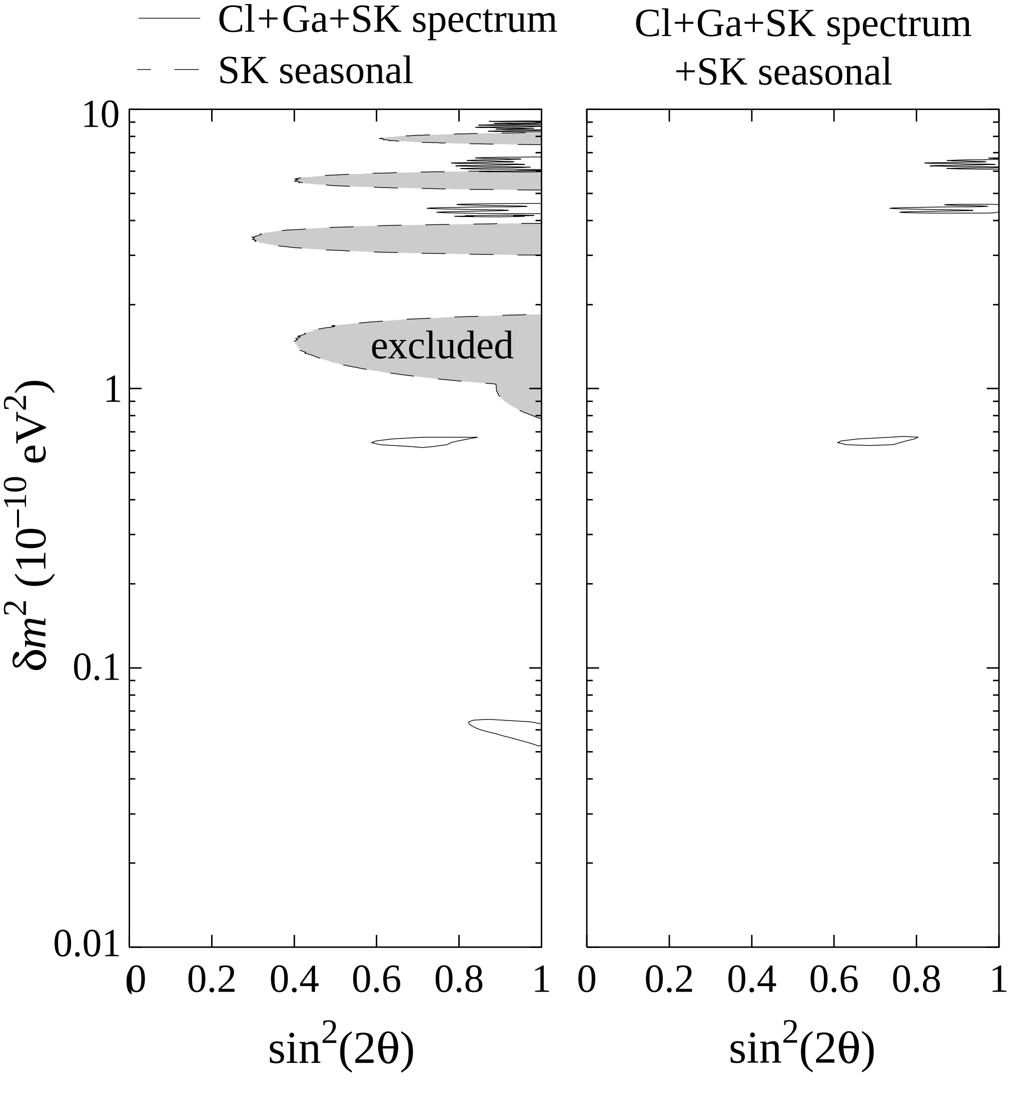
only ν_e

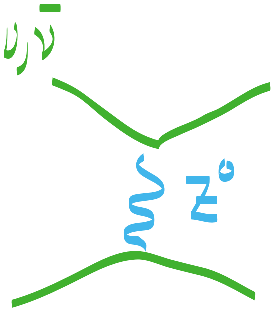
Solar neutrinos appear
via ν_e interactions
E ~ 7 MeV





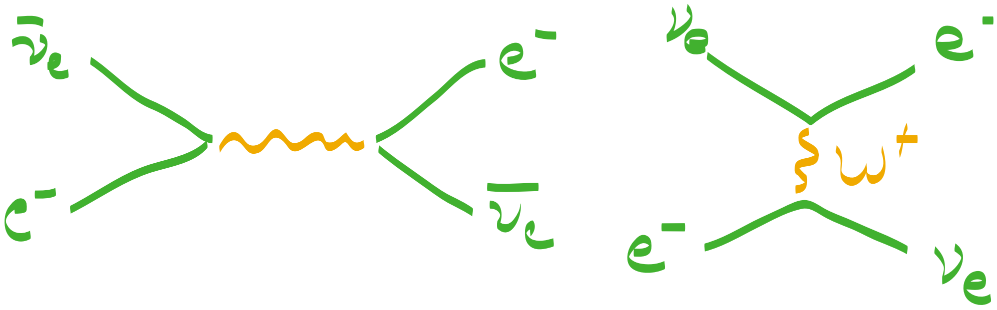
Oscillations on the 1 astronomical unit scale are still possible but seasonal variation due to earth's orbit can rule out some Δm^2





all ν can interact with matter

Other oscillation lengths are consistent with solar data!

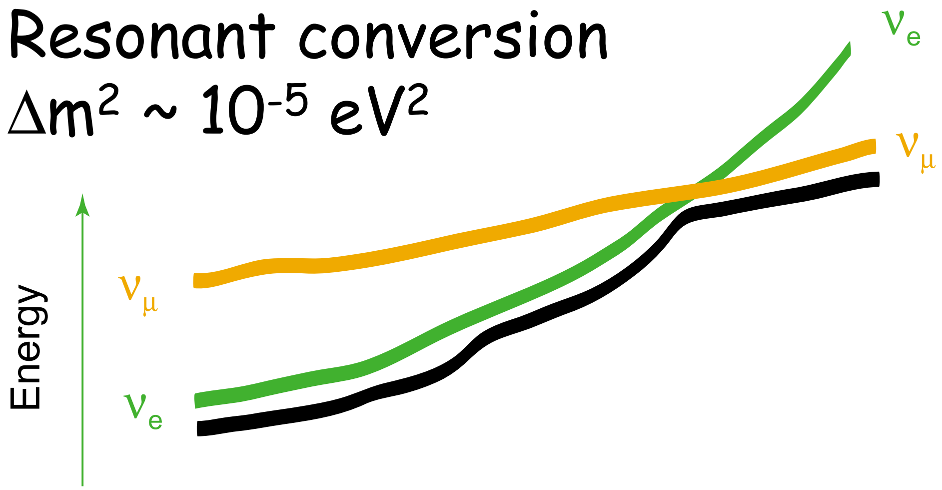


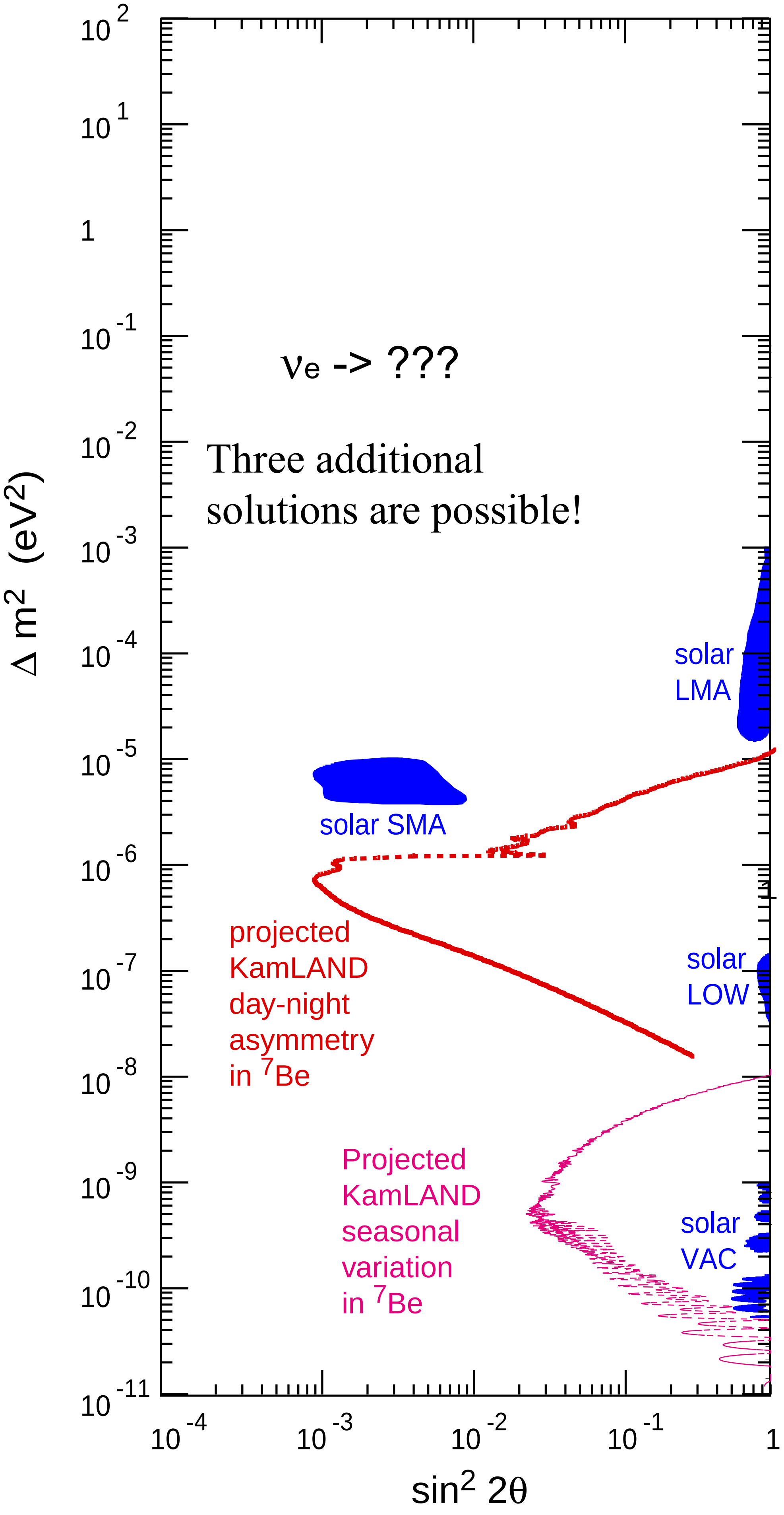
electron ν have additional interactions

As neutrinos pass through the sun, their $E = T + U$ changes.

Resonant conversion

$\Delta m^2 \sim 10^{-5}$ eV^2





Three additional solutions are possible!

Summary so far

- Solar neutrino experiments indicate a deficit in electron neutrinos once they get to the earth
- Solar models cannot accommodate this deficit.
- There could be oscillations on the scale of the earths orbit ($\Delta m^2 \sim 10^{-10}$)
- Or resonant oscillations in the sun with solutions

δm^2_{21} (eV^2)	5×10^{-5}	6×10^{-6}	1×10^{-7}
$\sin^2 2\theta_{solar}$	0.78	0.006	0.88

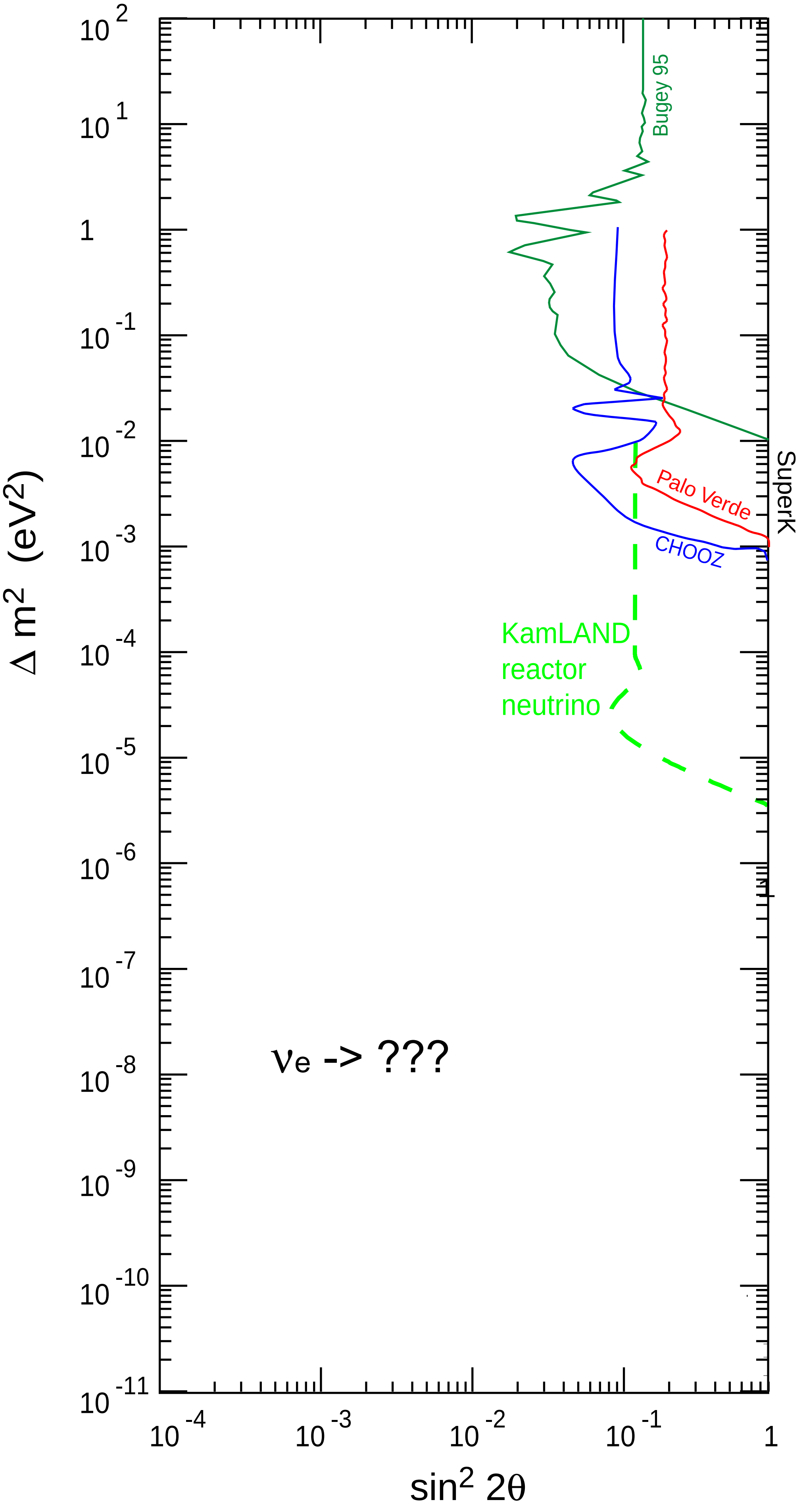
- But no experiment has seen conclusive variations with E/L

Reactor Experiments

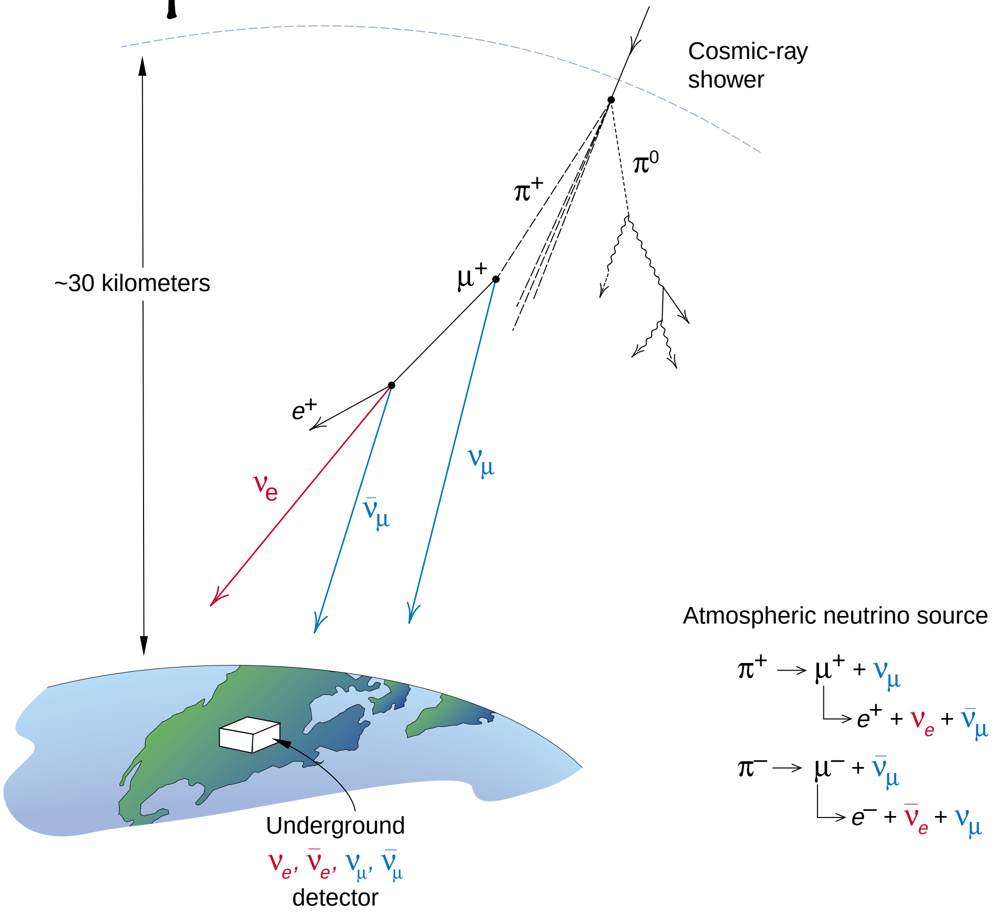
- Nuclear reactors produce very low energy anti-electron neutrinos. Current experiments have baselines of 1km or less but still set stringent limits.
- Future experiment: KAMLAND 2002
  - Large Liquid Scintillation detectors
  - Measure interaction rates as nuclear reactors in Japan go on and off
  - Effective baseline of 200 km
  - Sensitivity to ν_e-> ? with $\Delta M^2 > 10^{-6}$ eV^2

- Can test the Solar Large Mixing Angle solution

- Can also do solar neutrinos

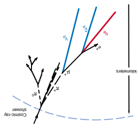

10 2
10 1
1
10 -1
10 -2
10 -3
10 -4
10 -5
10 -6
10 -7
10 -8
10 -9
10 -10
10 -11
Δ m2 (eV2)
10 -4
10 -3
10 -2
10 -1
1
sin2 2θ
Bugey 95
Palo Verde
CHOOZ
SuperK
KamLAND
reactor
neutrino
νe -> ???

Atmospheric Neutrinos



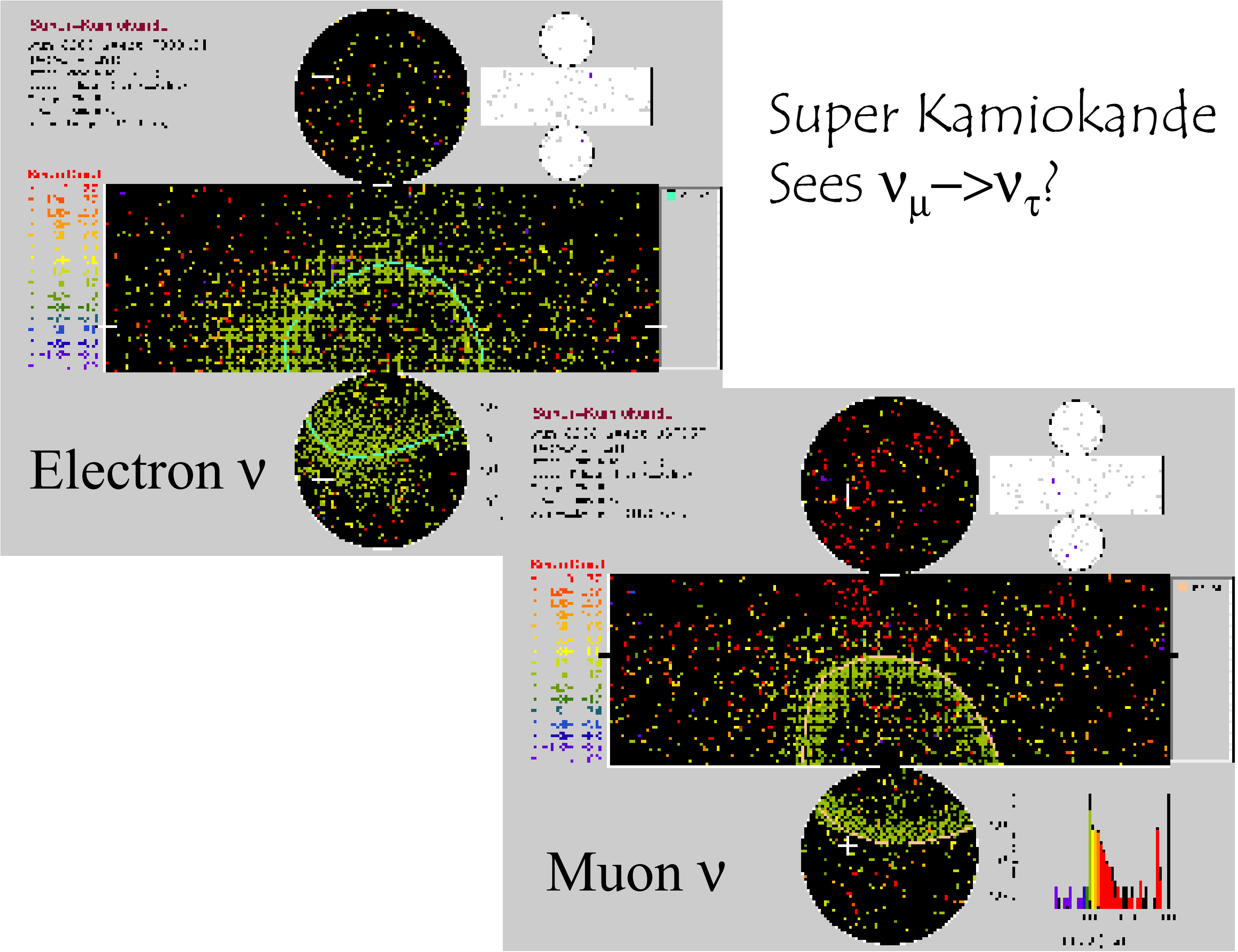
Atmospheric neutrino source

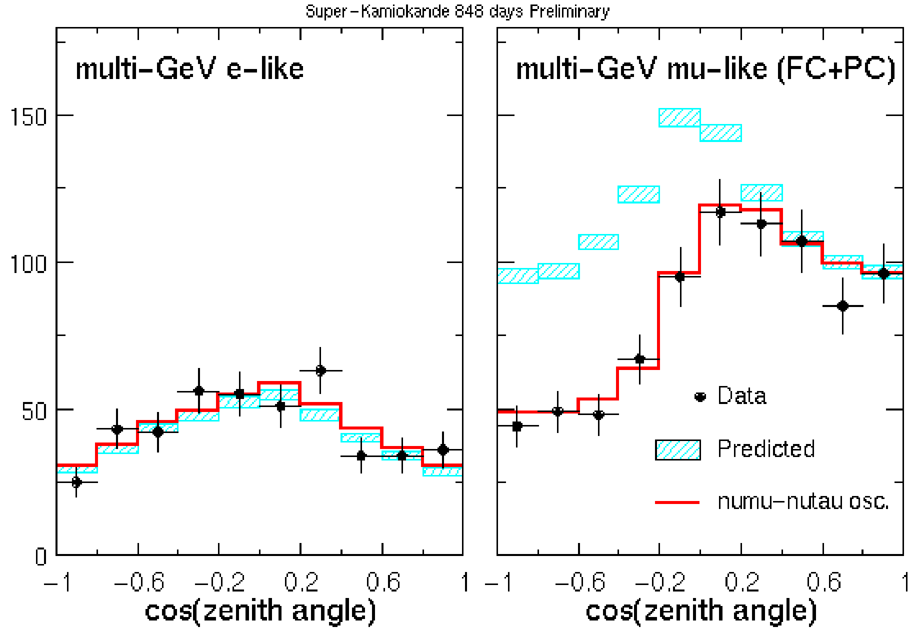
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

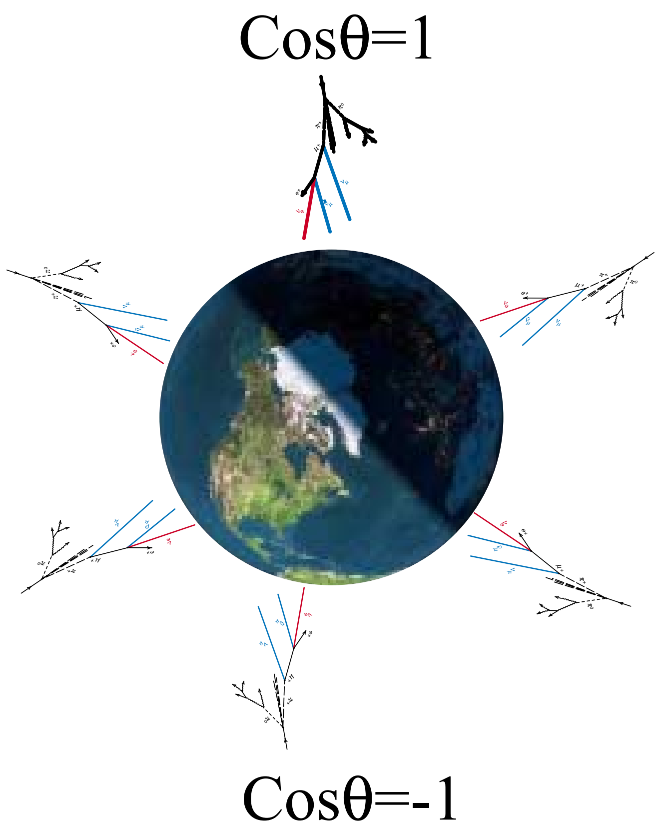


Other side of earth > 10000 km way

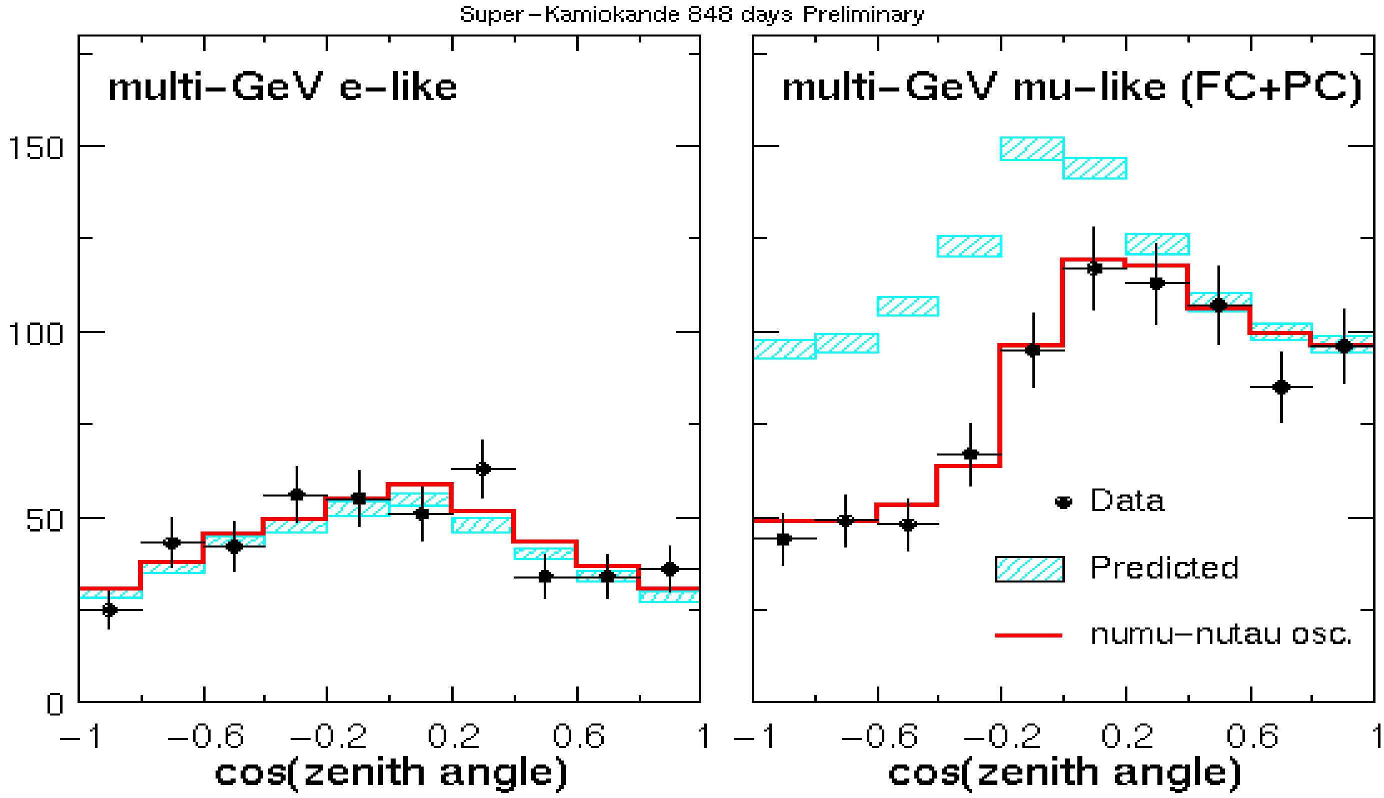
Super Kamiokande Sees ν_μ->ν_τ?





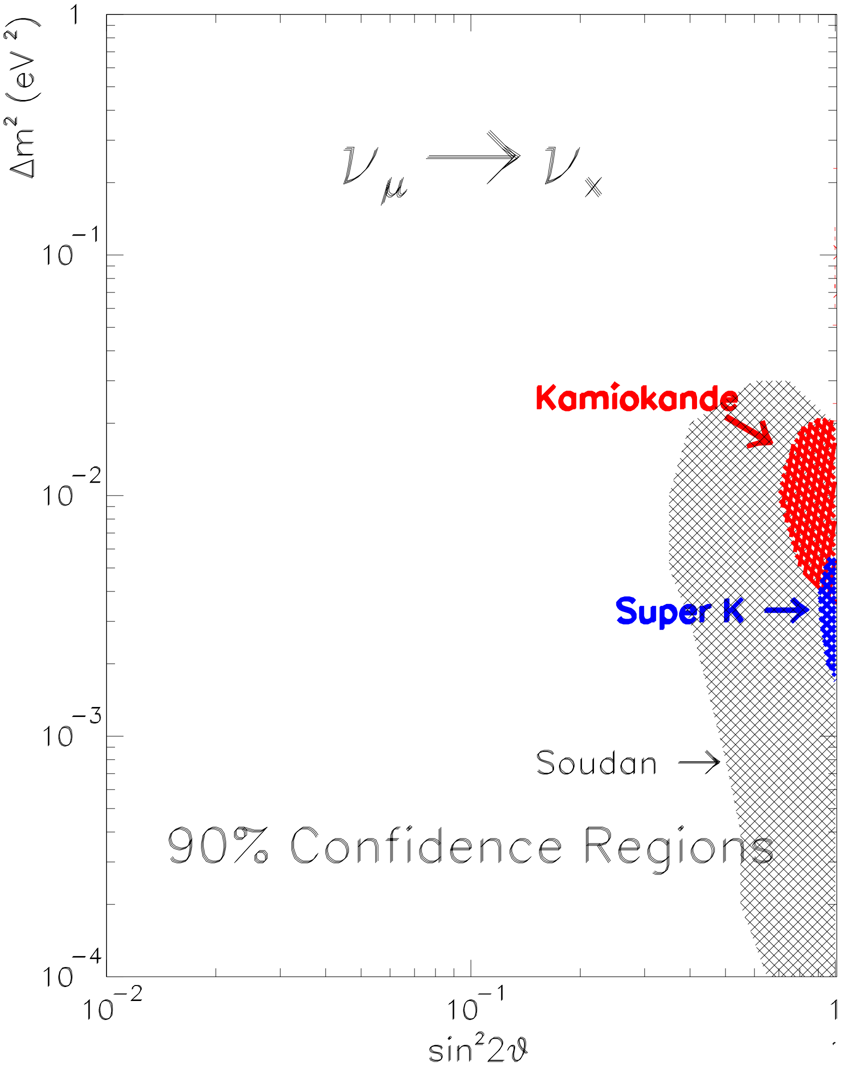


SuperK sees baselines from 20km to 14000km



Consistent with ν_μ->ν_τ or ν_μ -> ?

Atmospheric results



- Consistent with oscillations with

  $\Delta M^2 \sim 0.0035$ eV^2

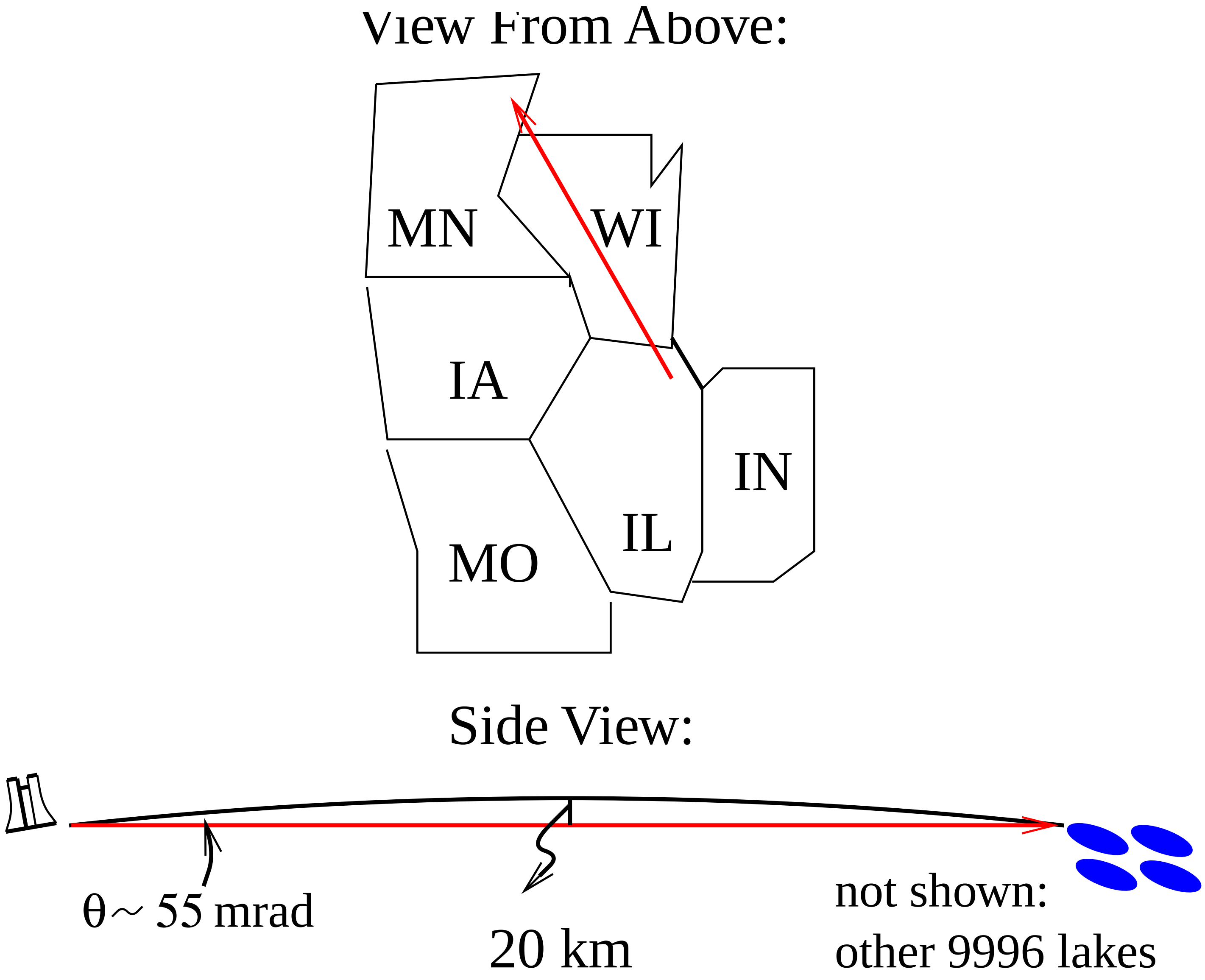
  - $\sin^2 2\theta \sim 0.8$-1

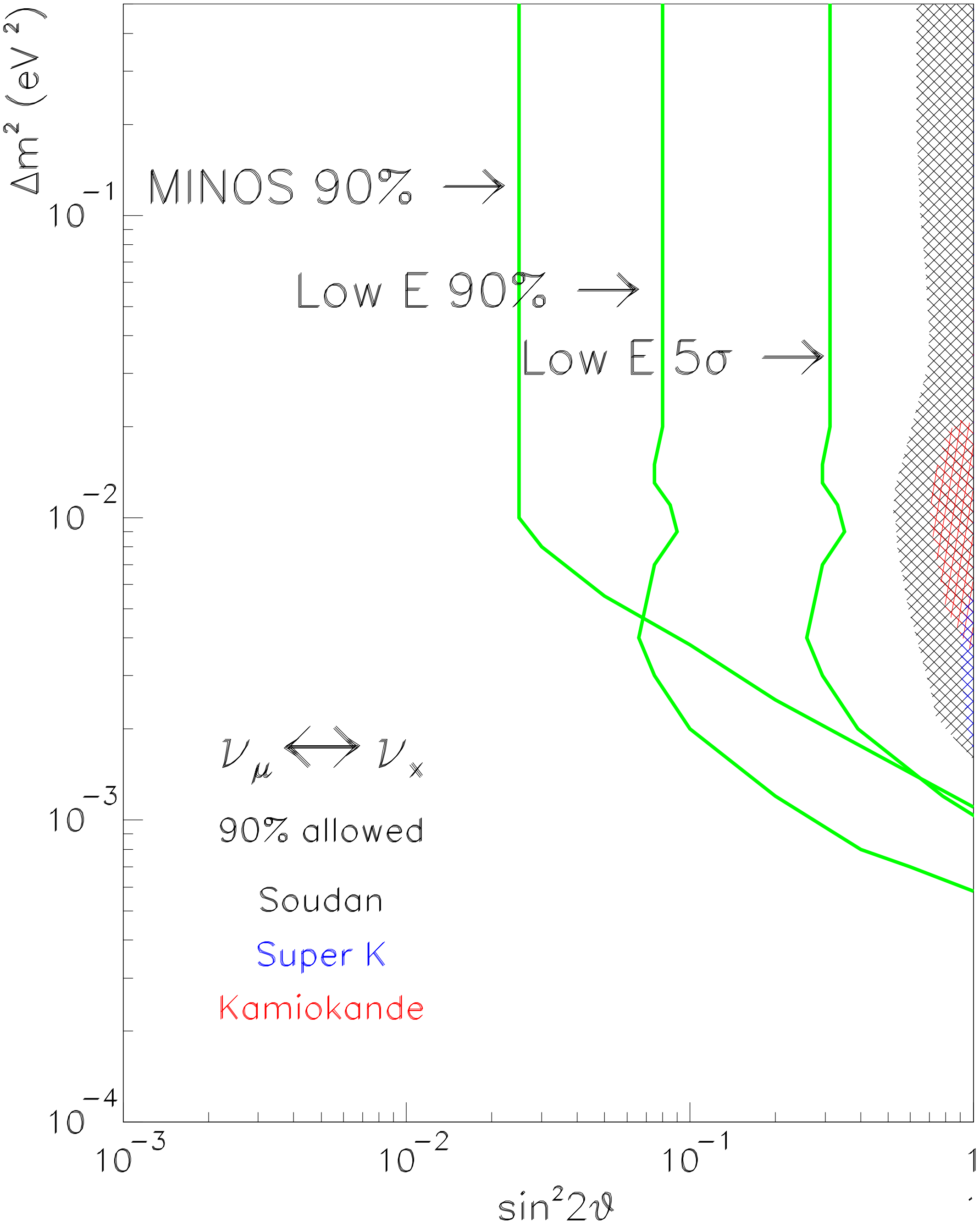
This is can be seen with accelerators with longbaselines

- K2K – Running Now!
  - Aim a ~ 1-2GeV beam from KEK to Super-K, about 200 km
    - Running
    - Sees 3 events where expected 12?
- CERN to Gran Sasso – 2003-4
  - About 700 km
  - Opera
    - Emulsions to see $\nu\mu \rightarrow \nu\tau$
  - Icanoe
    - Liquid Argon to see $\nu\mu \rightarrow \nu e$
- Fermilab to Soudan –2003
  - About 700 km
  - MINOS
    - Iron –Fe for high rate, $\nu\mu \rightarrow \nu e$

Steel-Scintillator

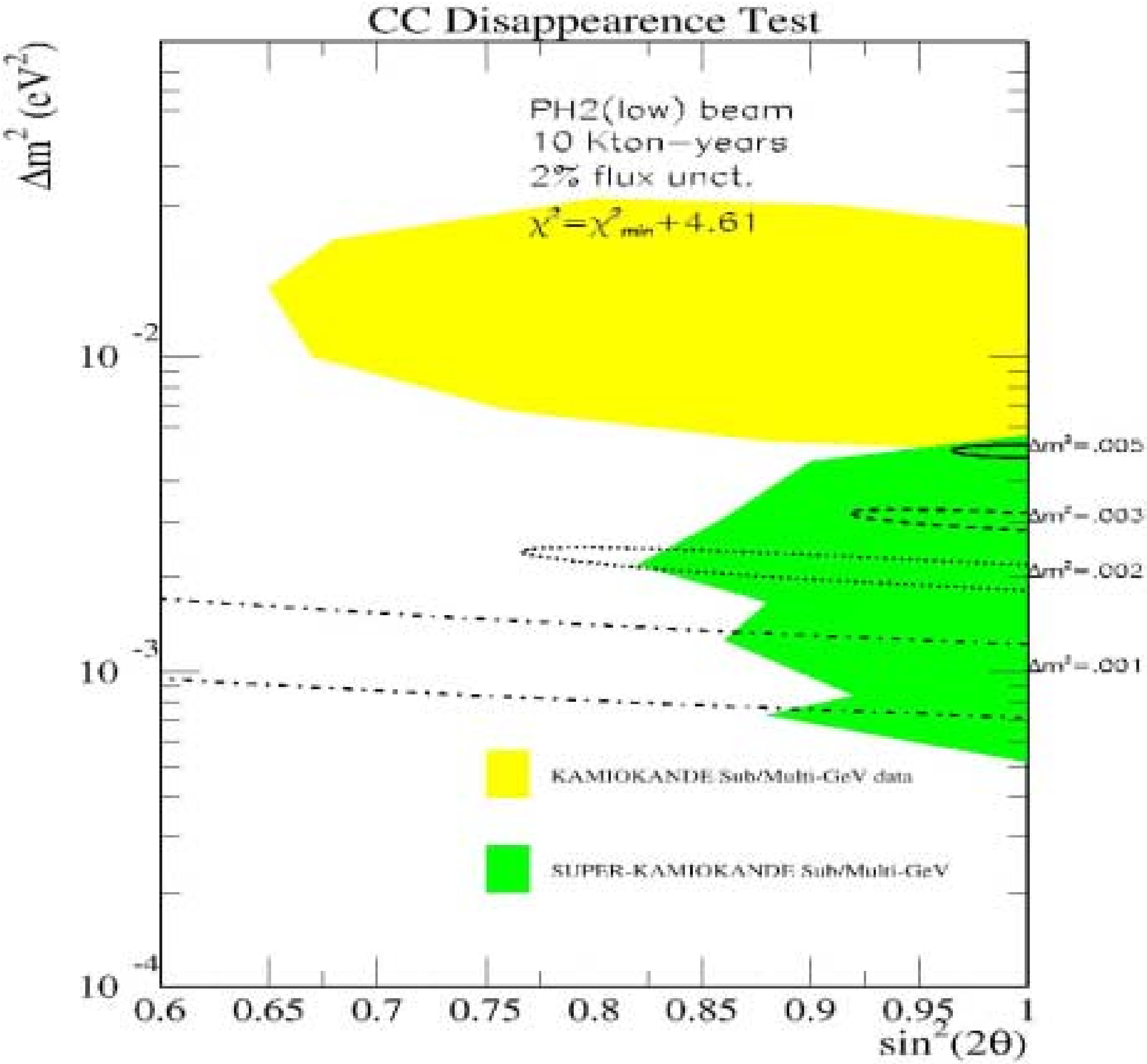
MINOS


View From Above:
MN
WI
IA
IN
IL
MO
Side View:
θ~ 55 mrad
20 km
not shown:
other 9996 lakes

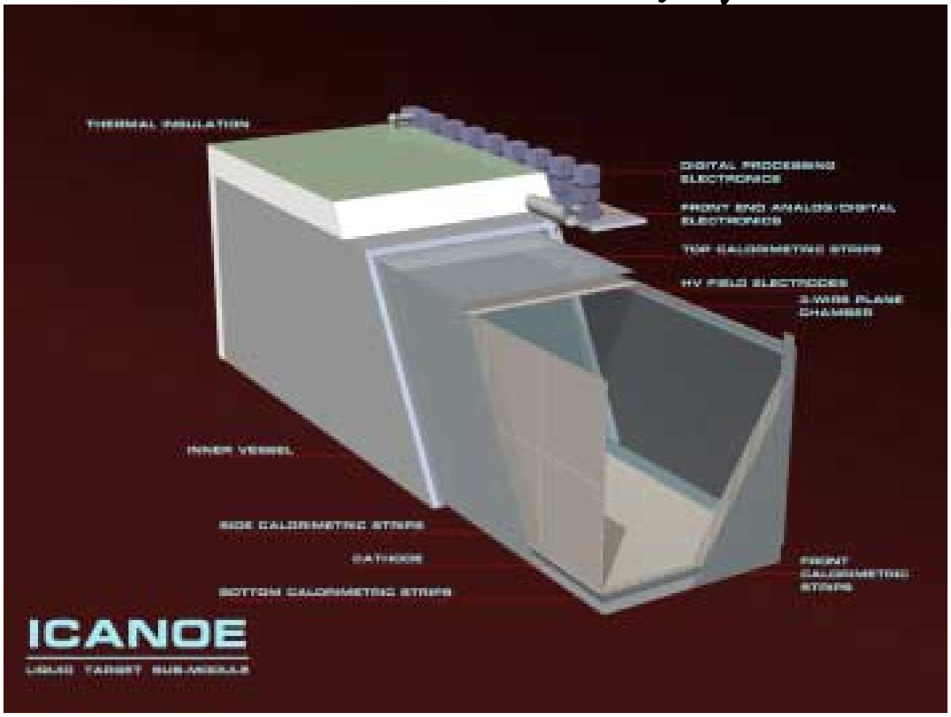


Δm^2 (eV^2)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\vartheta$
MINOS 90% →
Low E 90% →
Low E 5σ →
$\nu_\mu \leftrightarrow \nu_x$
90% allowed
Soudan
Super K
Kamiokande

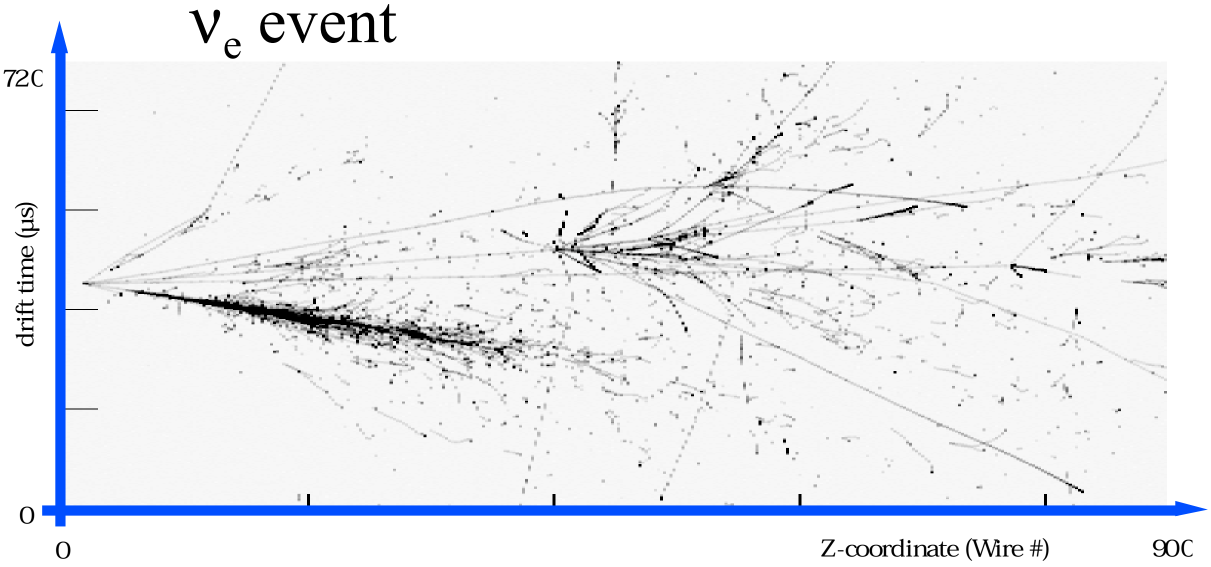
K2K, Minos and Cern experiments are very likely to measure parameters quite accurately



Liquid Argon with drift readout

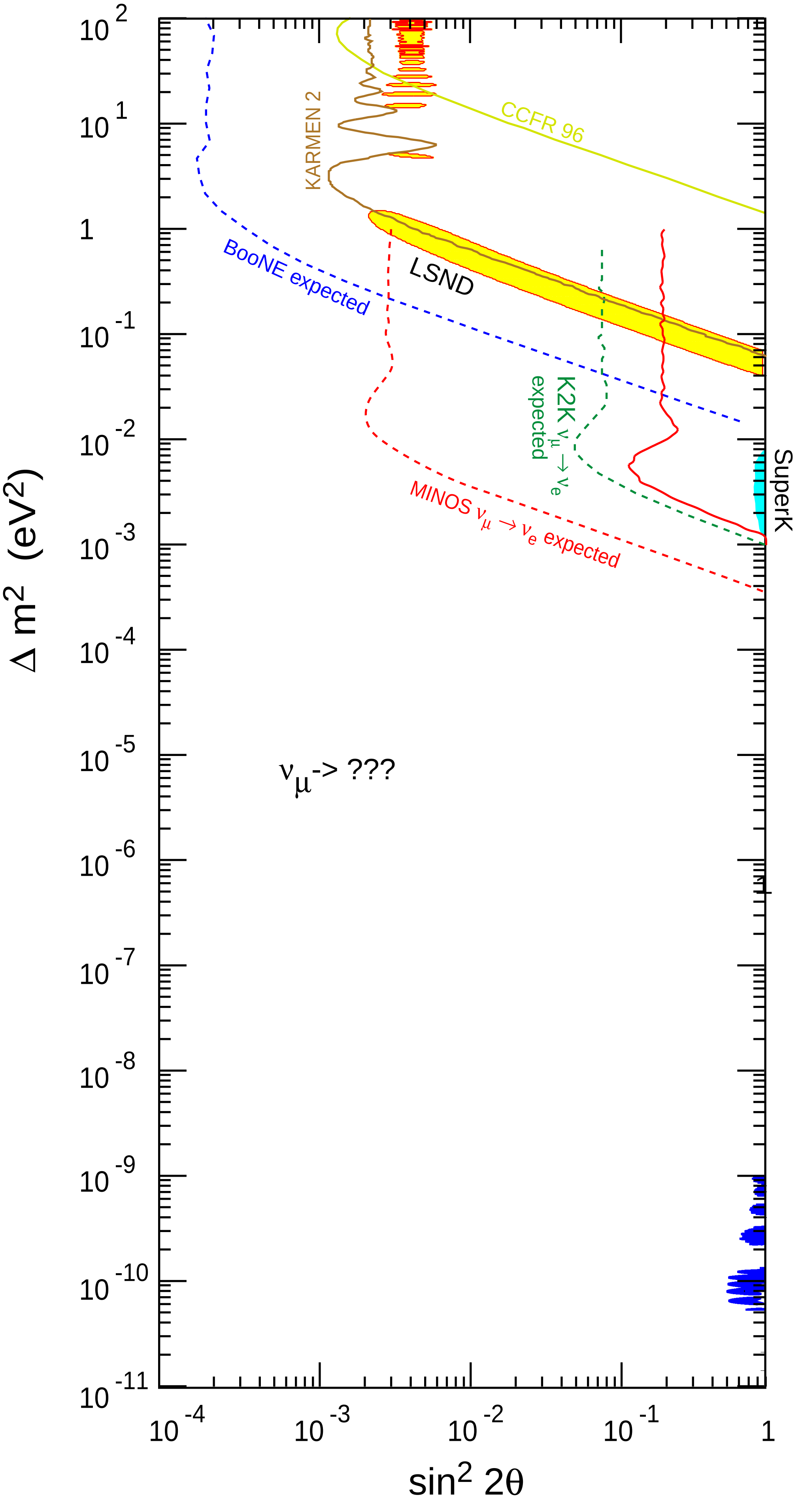


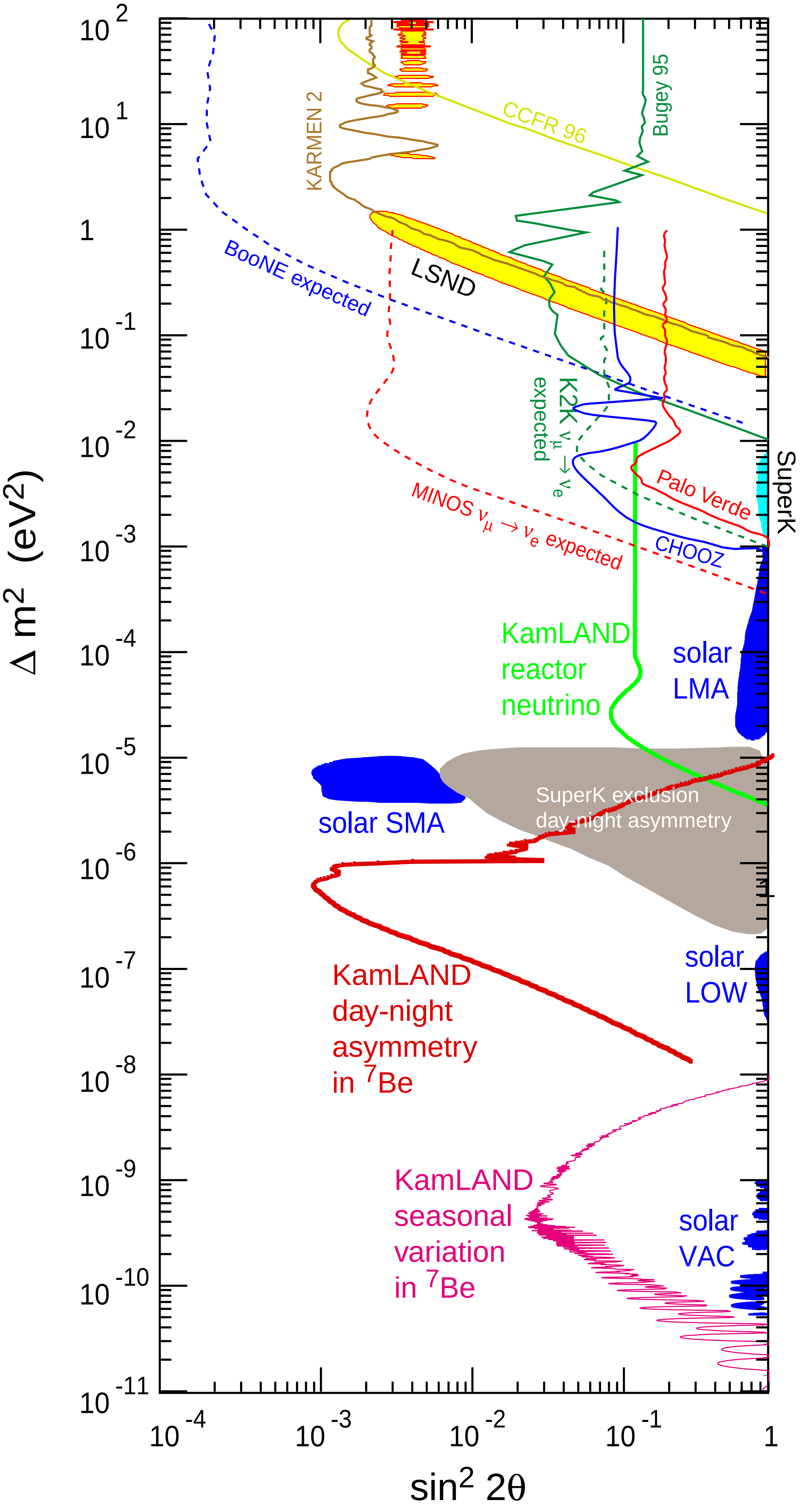
ν_e event



Situation so far

- Solar neutrinos consistent with mixing angles for electron neutrinos below 10^{-4} eV^2
- Atmospheric neutrinos consistent with mixing angles for muon neutrinos ~ 3.5 10^{-3} eV^2 and no electron mixing at that scale.
- These can be accommodated in a 3-flavor scheme – which is what we have anyways for quarks


10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Δm^2 (eV^2)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$
KARMEN 2
CCFR 96
LSND
BooNE expected
K2K $\nu_\mu \to \nu_e$ expected
MINOS $\nu_\mu \to \nu_e$ expected
SuperK
ν_μ-> ???



10 2
10 1
1
10 -1
10 -2
10 -3
10 -4
10 -5
10 -6
10 -7
10 -8
10 -9
10 -10
10 -11
Δ m2 (eV2)
10 -4
10 -3
10 -2
10 -1
1
sin2 2θ
KARMEN 2
CCFR 96
Bugey 95
LSND
BooNE expected
K2K νμ → νe expected
Palo Verde
SuperK
MINOS νμ → νe expected
CHOOZ
KamLAND reactor neutrino
solar LMA
solar SMA
SuperK exclusion day-night asymmetry
solar LOW
KamLAND day-night asymmetry in 7Be
KamLAND seasonal variation in 7Be
solar VAC

Standard Model of Elementary Particles

Charge
mass,MeV

	3 Generations of Fermions			Force Carriers	
Quarks	2/3 u ~5	2/3 c ~1350	2/3 t 175000	0 g 0	Strong Interactions
	−1/3 d ~9	−1/3 s ~175	−1/3 b ~4500	0 γ 0	Electro-magnetism
Leptons	ν_1 0?	ν_2 0?	ν_3 0?	0 Z^0 91187	Weak Interactions
	e 0.511	μ 105.66	τ 1777.2	±1 $W^\pm$ 81400	

Masses are in MeV

July 1997