OUR CURRENT UNDERSTANDING OF MASS AND MIXING IN THE NEUTRINO SECTOR

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NEUTRINO MASS AND MIXING

I. Three Neutrinos.

- Neutrino production and interaction
- Three flavors
- Neutrinos and Antineutrinos

II. Neutrino Mass: Direct Searches

- Searches for ν mass in ν production

III. Neutrino Oscillations

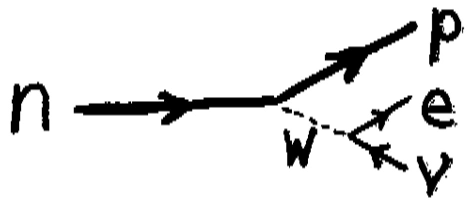
- Indirect probe of very small ν masses
- Experimental indications:
  - Atmospheric ν
  - LSND
  - Solar ν
- The current situation
- New experiments

IV. Concluding Remarks

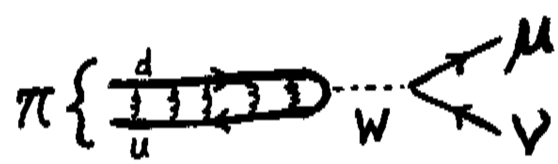
NEUTRINO PRODUCTION:

NEUTRINOS ARE PRODUCED IN WEAK INTERACTIONS:

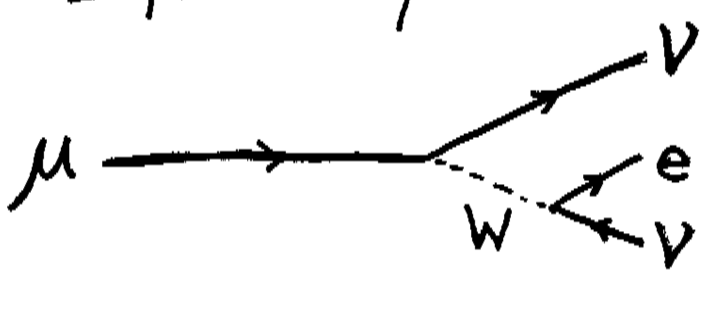
→ Nucleus or neutron β-decay:



→ Meson decay:



→ Lepton decay:

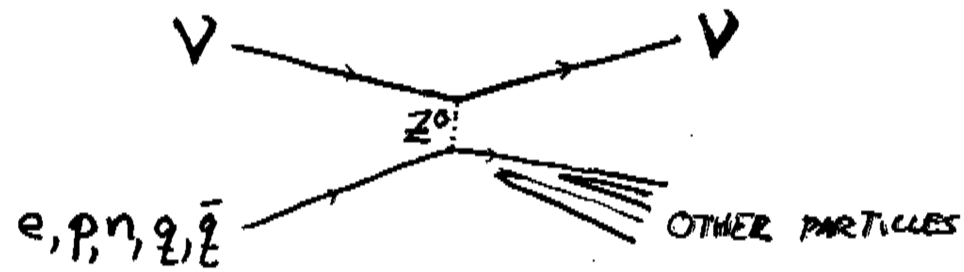


Exploit by making beams of mesons, muons which decay → NEUTRINO BEAMS

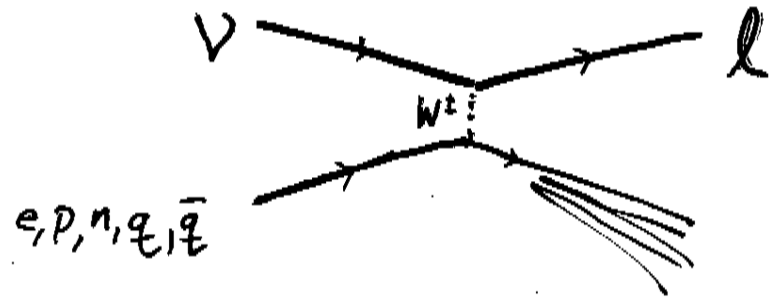
NEUTRINO INTERACTION:

TWO KINDS OF NEUTRINO INTERACTIONS:

① NEUTRAL CURRENT: NEUTRINO IN, NEUTRINO OUT.



② CHARGED CURRENT: NEUTRINO IN, CHARGED LEPTON OUT



CHARGED LEPTON ℓ FLAVOR IS SAME AS INCOMING NEUTRINO:

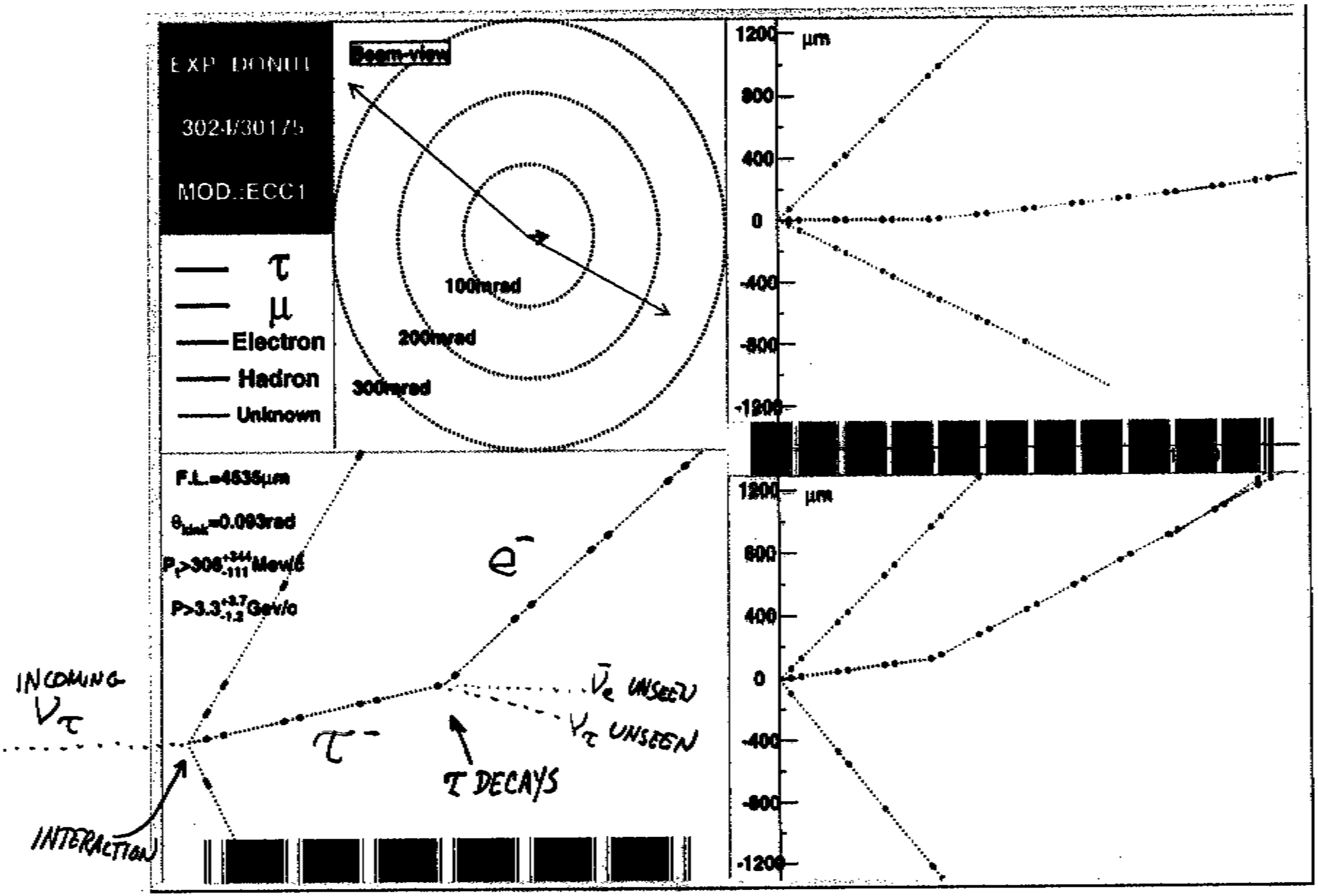
(COWAN/REINES, 1953) ν_e ONLY PRODUCES e^-

(BROOKHAVEN, 1962) $\nu_\mu \longrightarrow \mu^-$

(FERMILAB, 2000) $\nu_\tau \longrightarrow \tau^-$

IDENTIFICATION OF INTERACTION PRODUCTS IN CHARGED CURRENT PROCESSES ALLOWS MEASUREMENT OF ν FLAVOR.

FNAL E872: FIRST GLIMPSE OF ν_τ



ARE NEUTRINOS AND ANTINEUTRINOS DISTINGUISHABLE?

EXPERIMENTALLY:

π^+ beam decays:

$$\pi^+ \longrightarrow \mu^+ \nu_\mu \xrightarrow{\text{INTERACTS}} \mu^- \text{ ONLY}$$

NEUTRINOS

WE CALL THESE:

ANTINEUTRINOS

π^- beam decays:

$$\pi^- \longrightarrow \mu^- \bar{\nu}_\mu \longrightarrow \mu^+ \text{ ONLY}$$

BUT — THE "NEUTRINO" WAS PRODUCED IN A NEGATIVE HELICITY STATE BY THE PARITY-VIOLATING WEAK INTERACTION; THE "ANTINEUTRINO" HAS POSITIVE HELICITY ("RIGHT-HANDED"). SINCE THE ν'S ALSO INTERACT IN A PARITY-VIOLATING WAY, THEY PRODUCE DIFFERENT-SIGNED MUONS.

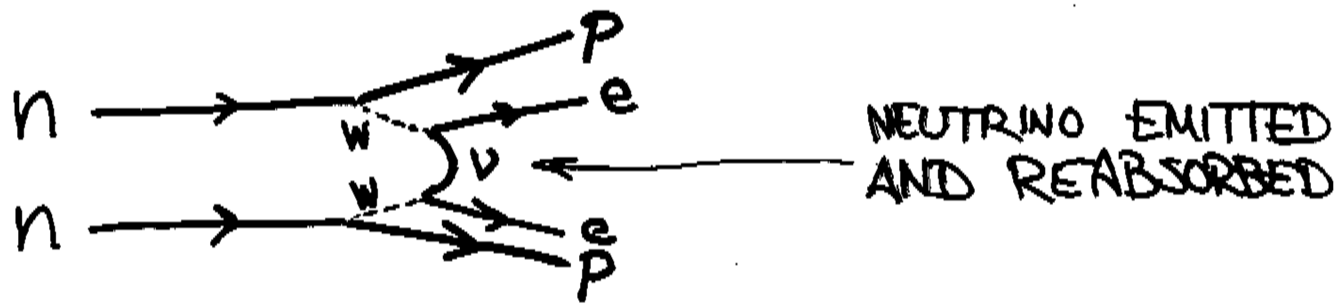
DO WE NEED ν AND $\bar{\nu}$? ("DIRAC" PARTICLE)

OR, ARE THEY SIMPLY DIFFERENT HELICITY STATES OF THE SAME PARTICLE? ("MAJORANA" PARTICLE)

TO ANSWER THIS QUESTION, WE NEED TO STOP A NEUTRINO, TURN IT AROUND, AND SEE IF IT BEHAVES LIKE AN ANTINEUTRINO:

NUCLEAR "NEUTRINOLESS DOUBLE BETA DECAY."

TWO NEUTRONS IN A NUCLEUS DECAY SIMULTANEOUSLY:



THIS PROCESS CAN ONLY HAPPEN IF THE NEUTRINO IS A MAJORANA PARTICLE $(\nu = \bar{\nu})$.

PROCESS HAS NEVER BEEN OBSERVED; LIFETIME LIMITS IN $\gtrsim 10^{21}$ YEARS RANGE.

GIVEN THESE LIFETIME LIMITS, ANY MAJORANA NEUTRINO WHICH COUPLES TO THE ELECTRON MUST HAVE MASS $<$ ~A FEW eV/c^2.

NEUTRINO MASS "DIRECT" SEARCHES

- KINEMATICS OF NEUTRINO PRODUCTION SENSITIVE TO ν MASS
- ν_e : TRITIUM BETA DECAY
- ν_μ : PION DECAY AT REST
- ν_τ : TAU DECAY AT e^+e^- COLLIDERS

ν_e MASS MEASUREMENT:

TRITIUM BETA DECAY

$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

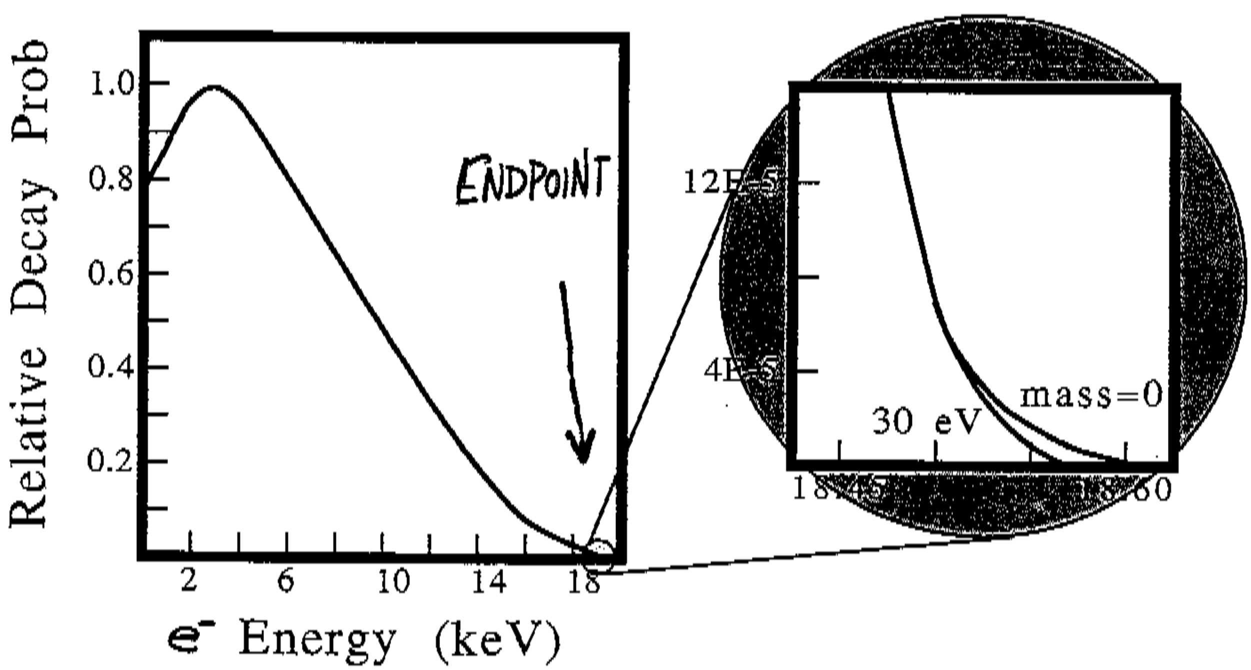
$$Q = 18.6\ keV - m_\nu$$

kinetic energy release

ELECTRON KINETIC ENERGY RANGES FROM 0 TO 18.56 keV "ENDPOINT"

IF ν_e MASS > 0, ENDPOINT ENERGY DROPS:

ELECTRON SPECTRUM

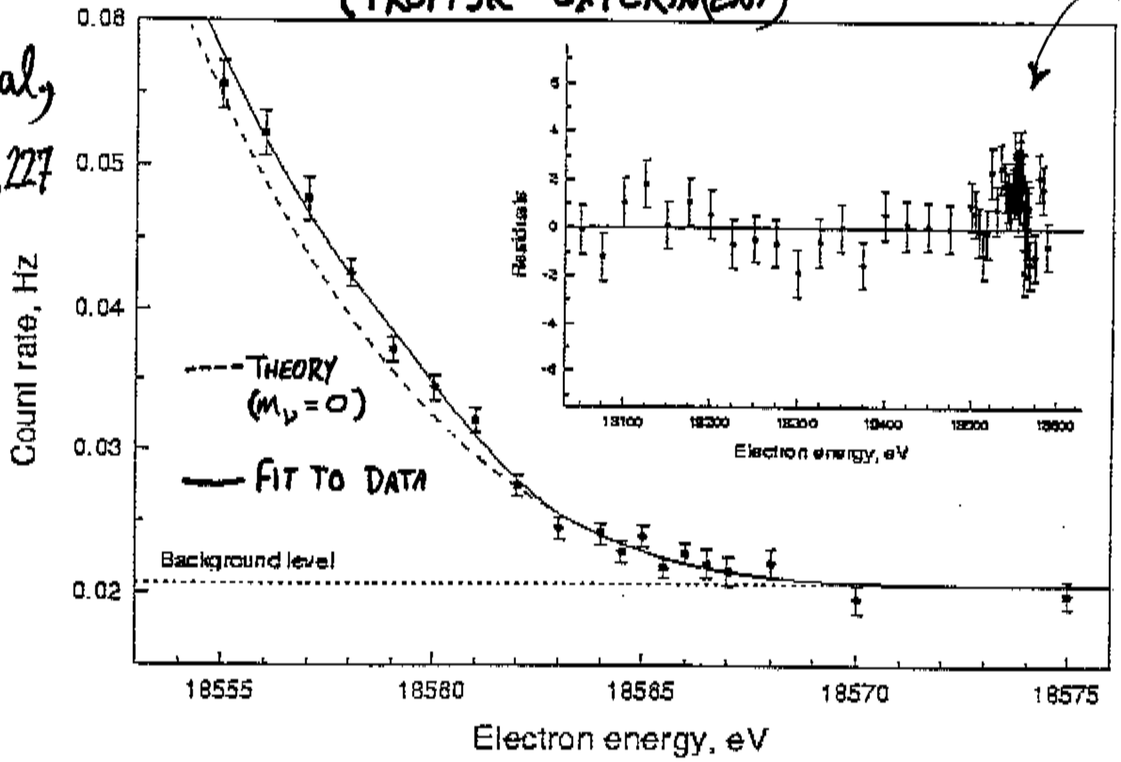


ν_e MASS FROM ^3H β-DECAY

e^- SPECTRUM NEAR ENDPOINT (TROITSK EXPERIMENT)

V.M. Lobashev et al, Phys. Lett. B460, 227

Anomalous excess



Neutrino mass should cause data to fall below theory near endpoint: ANOMALOUS EXCESS NOT WELL UNDERSTOOD.

FIT GIVES SIGNIFICANTLY NEGATIVE m_ν^2; DESPITE UNPHYSICAL RESULT, CAN PLACE LIMIT

$$m_{\nu_e} < 3\,\mathrm{eV}/c^2 \quad \text{(PDG)}$$

ν_μ MASS MEASUREMENT

BASIC IDEA:

PRODUCE π^+ IN TARGET; ALLOW π^+ TO COME TO REST AND DECAY:

IGNORING RADIATIVE EFFECTS, DECAY IS 2-BODY:

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

IN π^+ REST FRAME, μ MOMENTUM MONOCHROMATIC:

$$P_\mu \cong \frac{1}{2m_\pi}\sqrt{(m_\pi^2 - m_\mu^2)^2 - 4m_\mu^2 m_\nu^2}$$

$$= 29.791816 \text{ MeV/c} \quad m_\nu = 0$$
$$= 29.791719 \text{ MeV/c} \quad m_\nu = 0.1 \text{ MeV/c}^2$$

0.1 MeV ν_μ mass $\Longrightarrow$ only 10^{-4} MeV shift in p_μ; p_μ is also sensitive to uncertainty in m_π.

Even with spectacularly precise p_μ measurement, can only limit $m_{\nu_\mu} < 0.19$ MeV/c^2. (10^5 worse than ν_e limit!)

ν_τ MASS MEASUREMENT:

USE RARE, LOW-Q τ DECAYS:

$$\tau^- \to \nu_\tau \pi^+ \pi^+ \pi^- (\pi^-)(\pi^-)(\pi^0)$$

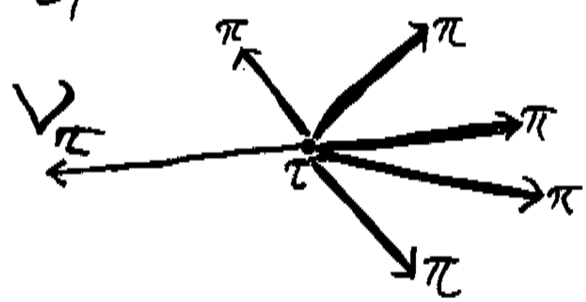
$m(5\pi) = 698$ MeV/
$m(\tau) = 1777$ MeV/c

Source of τ: e^+e^- collisions

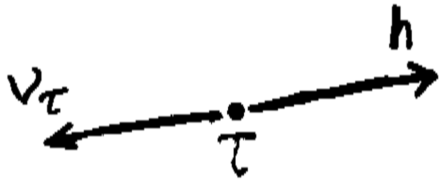
- on Z^0 resonance ($E_\tau = 45$ GeV)
- on $\Upsilon(4S)$ ($b\bar{b}$) ($E_\tau = 5.3$ GeV)

SAME BASIC PRINCIPLE AS ν_μ MEASUREMENT, BUT HERE THE RECOILING "BODY" IS THE ENTIRE 5-PION SYSTEM, AND ITS MASS MUST BE MEASURED ON AN EVENT-BY-EVENT BASIS:

DECAY
IN τ REST FRAME



IS INTERPRETED AS:



HADRONIC SYSTEM: $P_\nu = P_h$
COMBINED MOMENTUM, INVARIANT MASS OF ALL PIONS.

$\tau \to \nu_\tau + (\geq 5)\pi$ EVENTS NEAR KINEMATIC LIMIT

(ALEPH data, $E_{beam} = 45$ GeV)

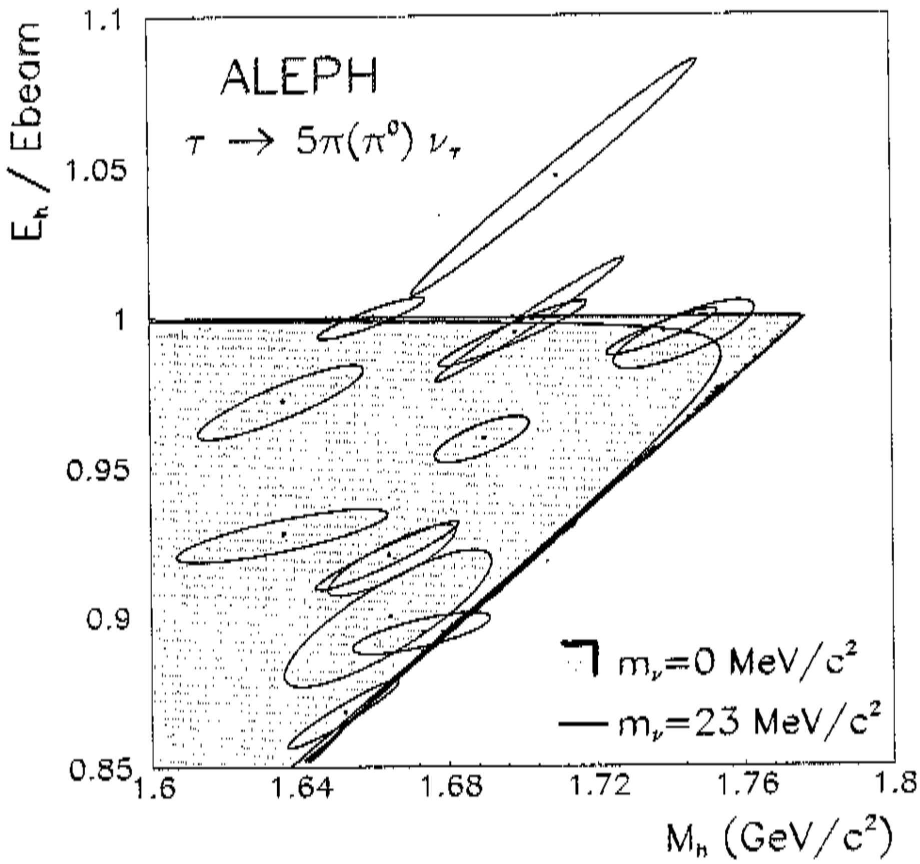


Figure 4: Distribution in the upper part of the (m_h, E_h) plane for $\tau^- \to 3\pi^-\ 2\pi^+\ (\pi^0)\ \nu_\tau$ candidates in the data. The grey area is the allowed region for a massless neutrino. The borderline of the allowed region for a 23 MeV/c^2 neutrino is also drawn. The only $\tau^- \to 3\pi^-\ 2\pi^+\ \pi^0\ \nu_\tau$ event in the plot is the one with the largest hadronic energy.

NO EVIDENCE FOR MASS SUPPRESSION NEAR ENDPOINT:

PDG LIMIT: $m_{\nu_\tau} < 18$ MeV/c^2

NEUTRINO OSCILLATIONS

- PROBE OF POSSIBLE VERY SMALL DIFFERENCES BETWEEN NU MASSES, PLUS MIXING WITH FLAVORS
- EXPERIMENTAL INDICATIONS OF OSCILLATIONS:
  - ATMOSPHERIC NEUTRINOS: SUPER-KAMIOKANDE
  - ACCELERATOR NEUTRINOS: LSND
  - SOLAR NEUTRINOS: HOMESTAKE AND SUCCESSORS
- THE CONFUSING CURRENT PICTURE
- CURRENT EFFORTS TO RESOLVE IT
  - K2K, MINOS
  - BooNE
  - SNO

NEUTRINO OSCILLATIONS: PROBE OF TINY MASSES

ASSUME THAT:

- There are TWO neutrinos (simpler than three)
- They are massive, and not degenerate
- The weak flavor eigenstates are NOT the same as the mass eigenstates:

A CLASSIC QUANTUM-MECHANICAL TWO-STATE SYSTEM:

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}}_{\text{FLAVORS}} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}}_{\text{MASSES}}$$

ν_1, ν_2 PHASES ROTATE AT DIFFERENT RATES:

$$|\nu_1\rangle \longrightarrow e^{-im_1 t} |\nu_1\rangle$$

SO... IF ONE STARTS AT T=0 WITH

$$|\nu_e(0)\rangle = \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle$$

IT EVOLVES:

$$|\psi(t)\rangle = \cos\theta\, e^{-im_1 t} |\nu_1\rangle + \sin\theta\, e^{-im_2 t} |\nu_2\rangle$$

THE INTERFERENCE GIVES RISE TO A TIME-DEPENDENT $|\nu_\mu\rangle$ COMPONENT:

SOLVING AND PLUGGING IN SENSIBLE UNITS:

Probability of finding ν_μ if neutrino was created as ν_e:

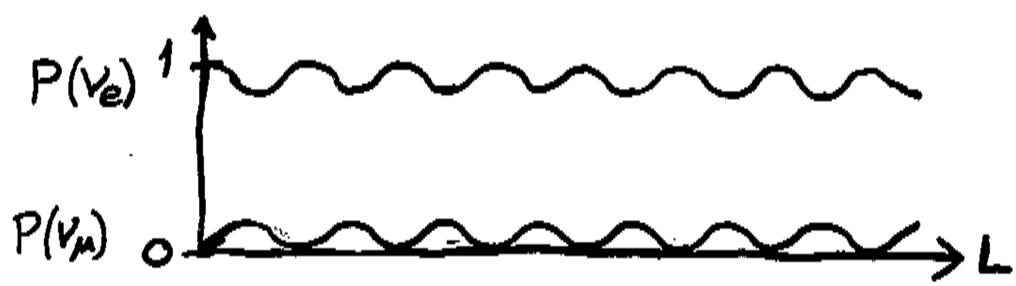
$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \, \sin^2\left[1.27\, \Delta m^2 \frac{L}{E}\right]$$

$\Delta m^2 = m_1^2 - m_2^2$ (eV^2/c^4)

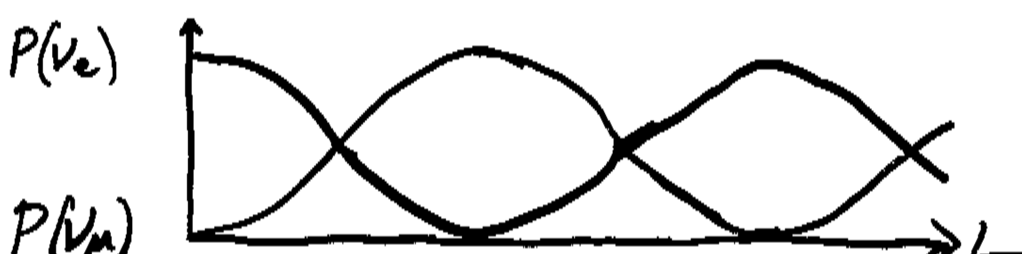
L = propagation length (km)

E = neutrino energy (GeV)

Large amplitude $\Leftrightarrow$ large $\sin^2 2\theta$ rapid oscillation $\Leftrightarrow$ large Δm^2

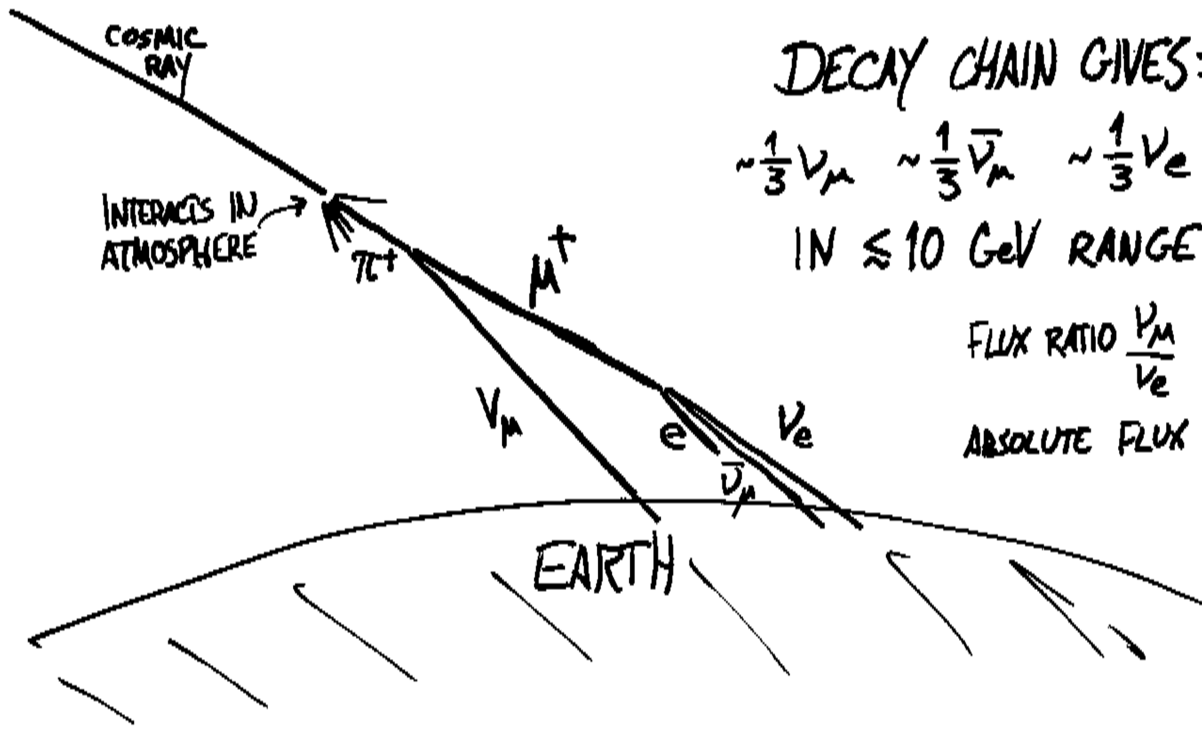


- Small θ
- Large Δm^2



- $\sin^2 2\theta = 1$
- Smaller Δm^2

• ATMOSPHERIC NEUTRINOS



DECAY CHAIN GIVES:

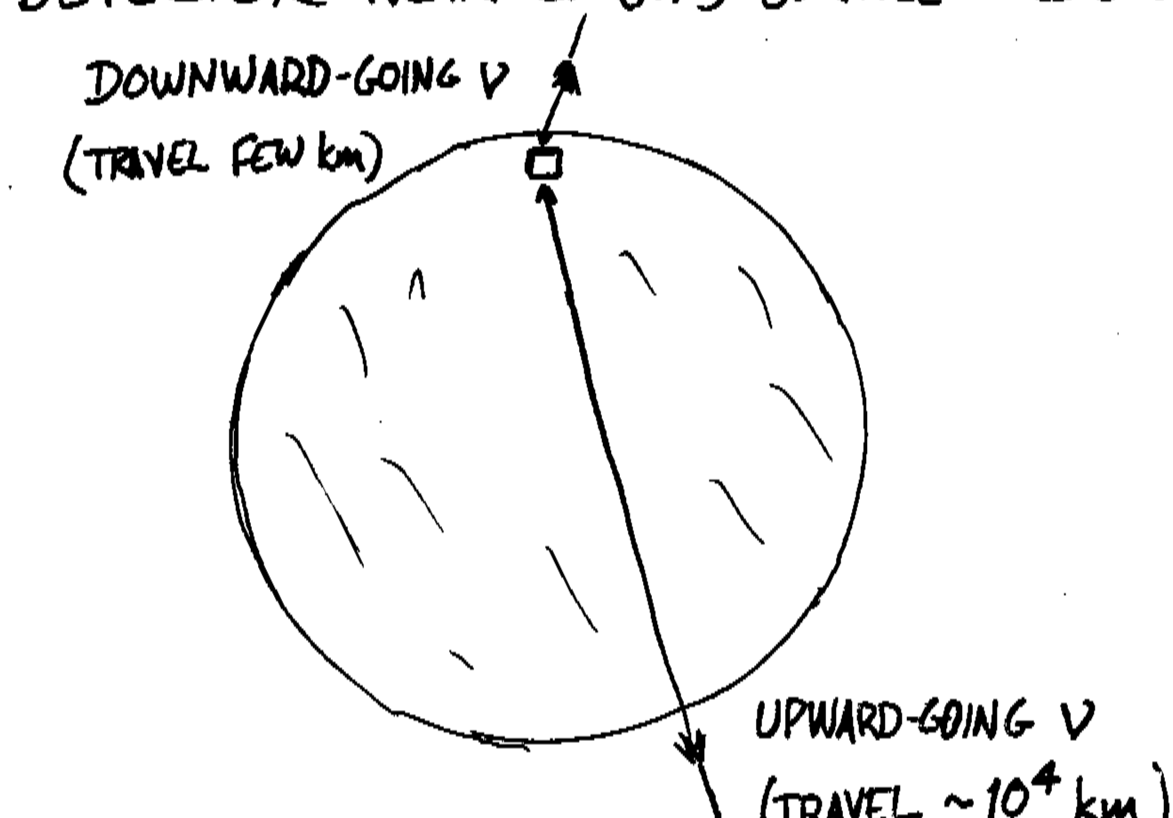
$\sim\frac{1}{3}\nu_\mu \quad \sim\frac{1}{3}\bar{\nu}_\mu \quad \sim\frac{1}{3}\nu_e$

IN $\lesssim 10$ GeV RANGE.

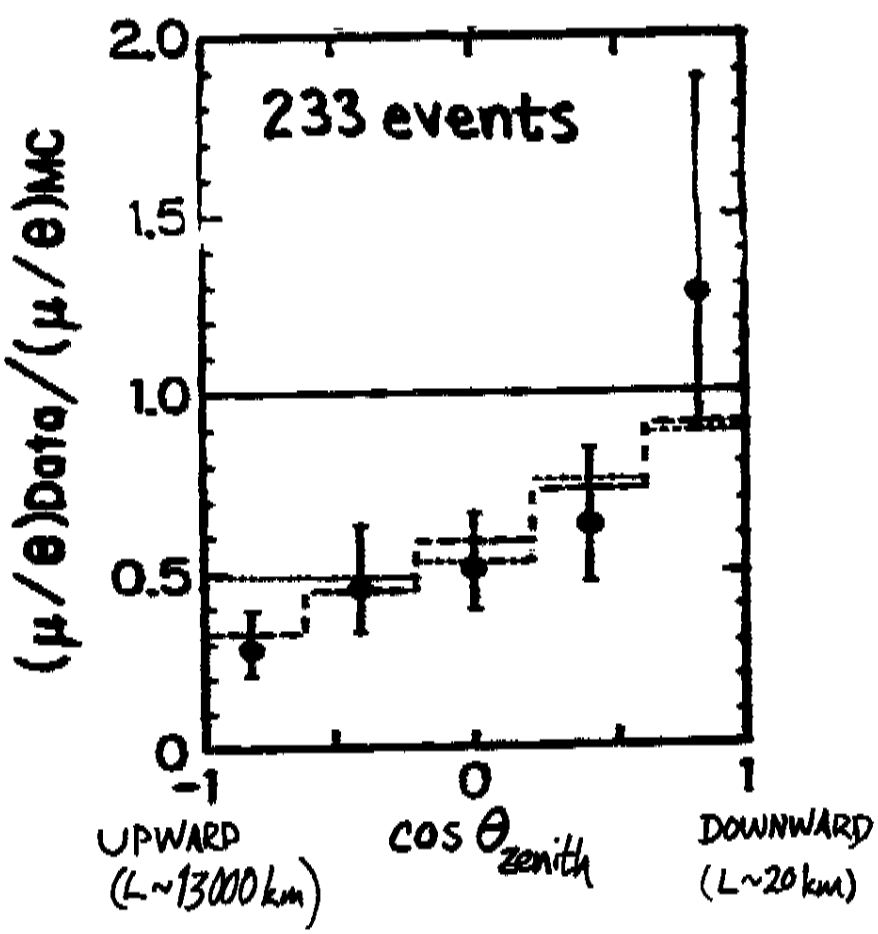
FLUX RATIO $\frac{\nu_\mu}{\nu_e}$ KNOWN TO ~5%

ABSOLUTE FLUX ~20%

A DETECTOR NEAR EARTH'S SURFACE WILL SEE:

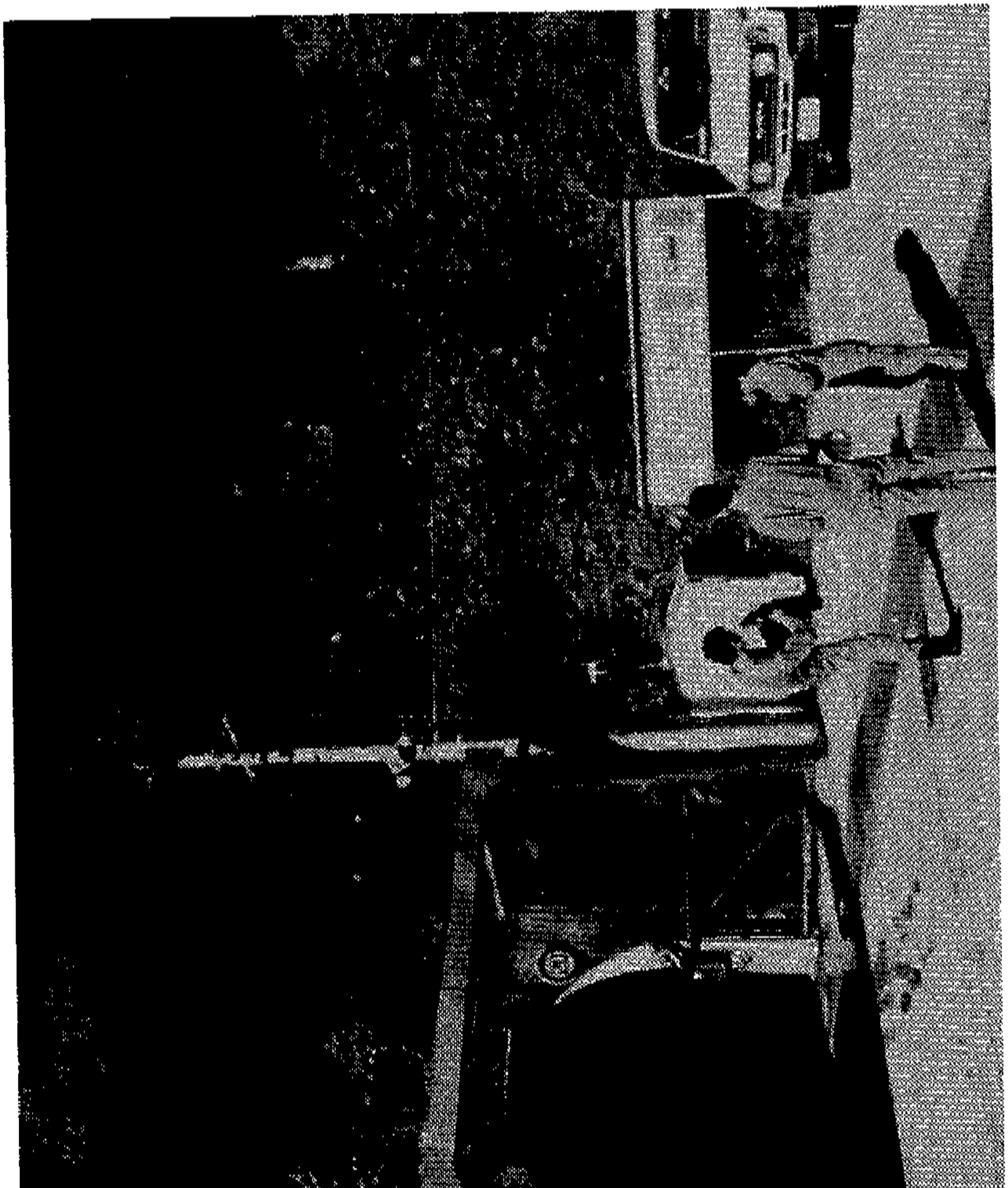


FOR ABOUT A DECADE, EXPERIMENTS HAVE SHOWN AN APPARENT DEFICIT OF ν_μ IN ATMOSPHERIC ν INTERACTIONS.



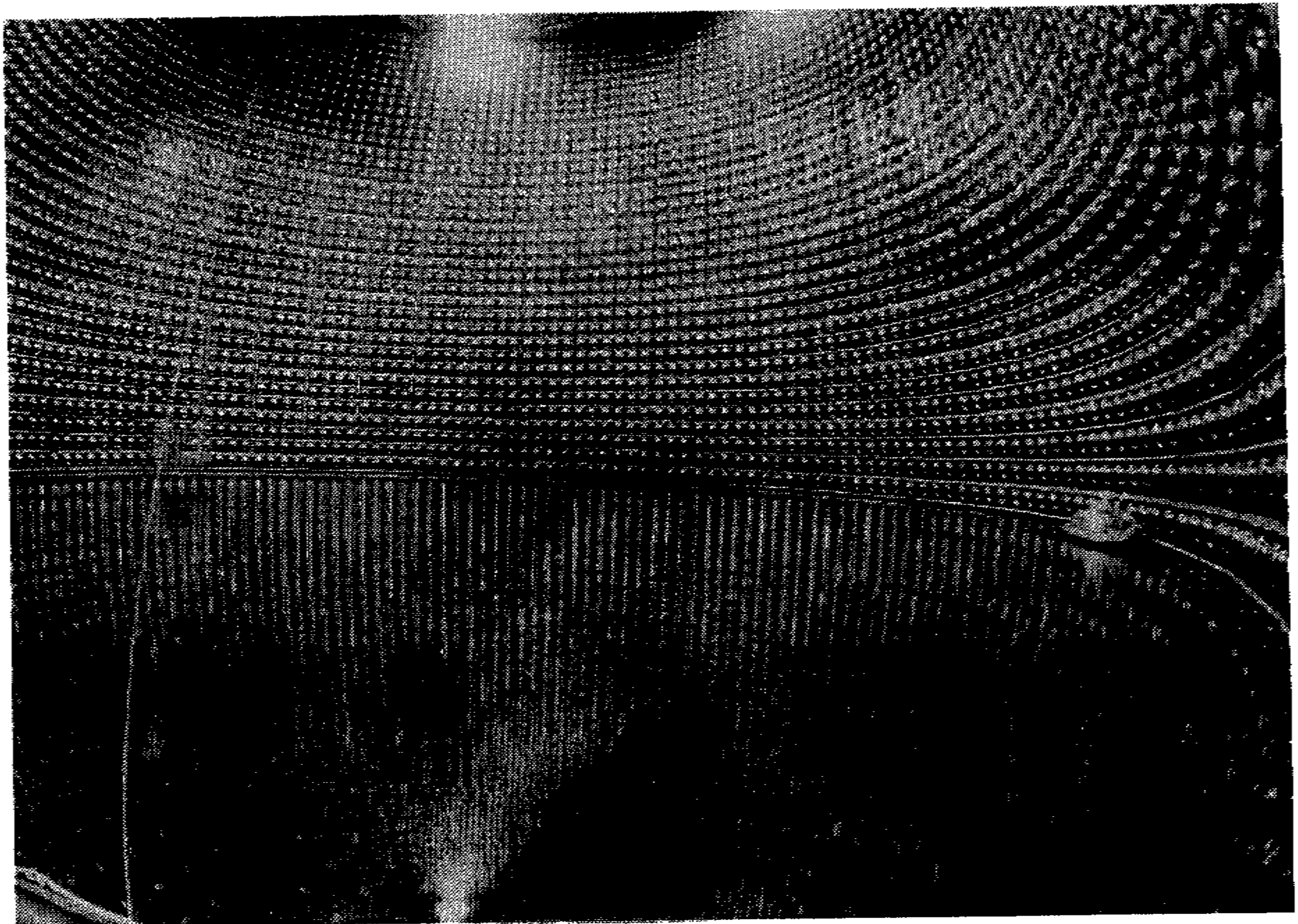
1994: KAMIOKANDE EXPERIMENT IN JAPAN INDICATES DEFICIT MAY BE DIRECTIONAL — THIS IS EVIDENCE FOR L-DEPENDENCE OF NEUTRINO FLAVOR (EXPECTED IN OSCILLATION SCENARIO)

SUPER-KAMIOKANDE LAB



(ABOVE-GROUND ENTRANCE)

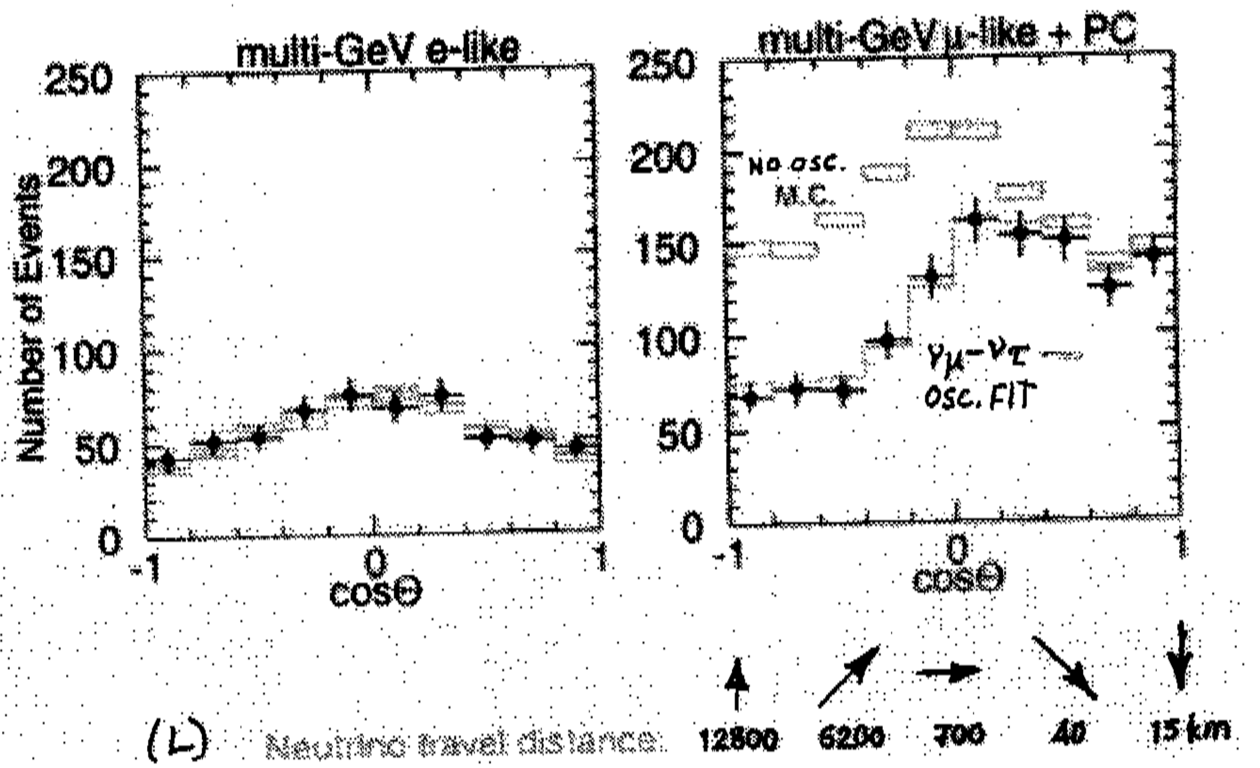
1996: WATER ČERENKOV DETECTOR SUPER-KAMIOKANDE



50,000 tons water (target and active detector); 11,200 20" photomultipliers

THREE YEARS' DATA: SUPER-K. 1996-99

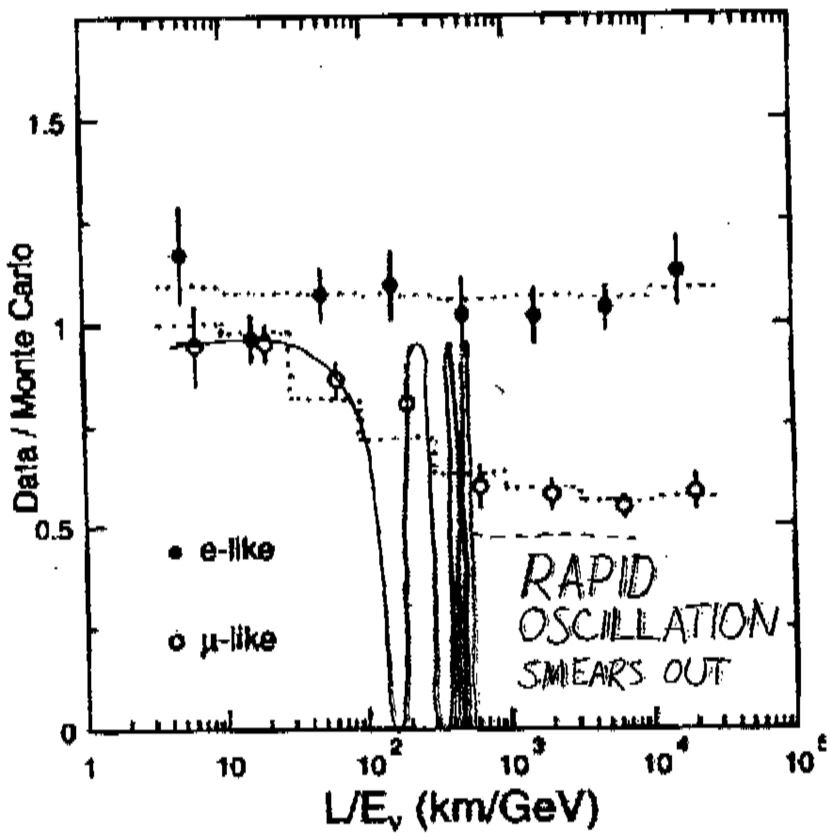
Up-Down Asymmetry



THE ANGULAR-DEPENDENCE IS <u>REAL</u>.

- NO STANDARD-MODEL PROCESS ALLOWS ν_μ TO "DISAPPEAR" LIKE THIS.
- ONLY ν_μ VANISH — IN SIGNIFICANT NUMBERS.

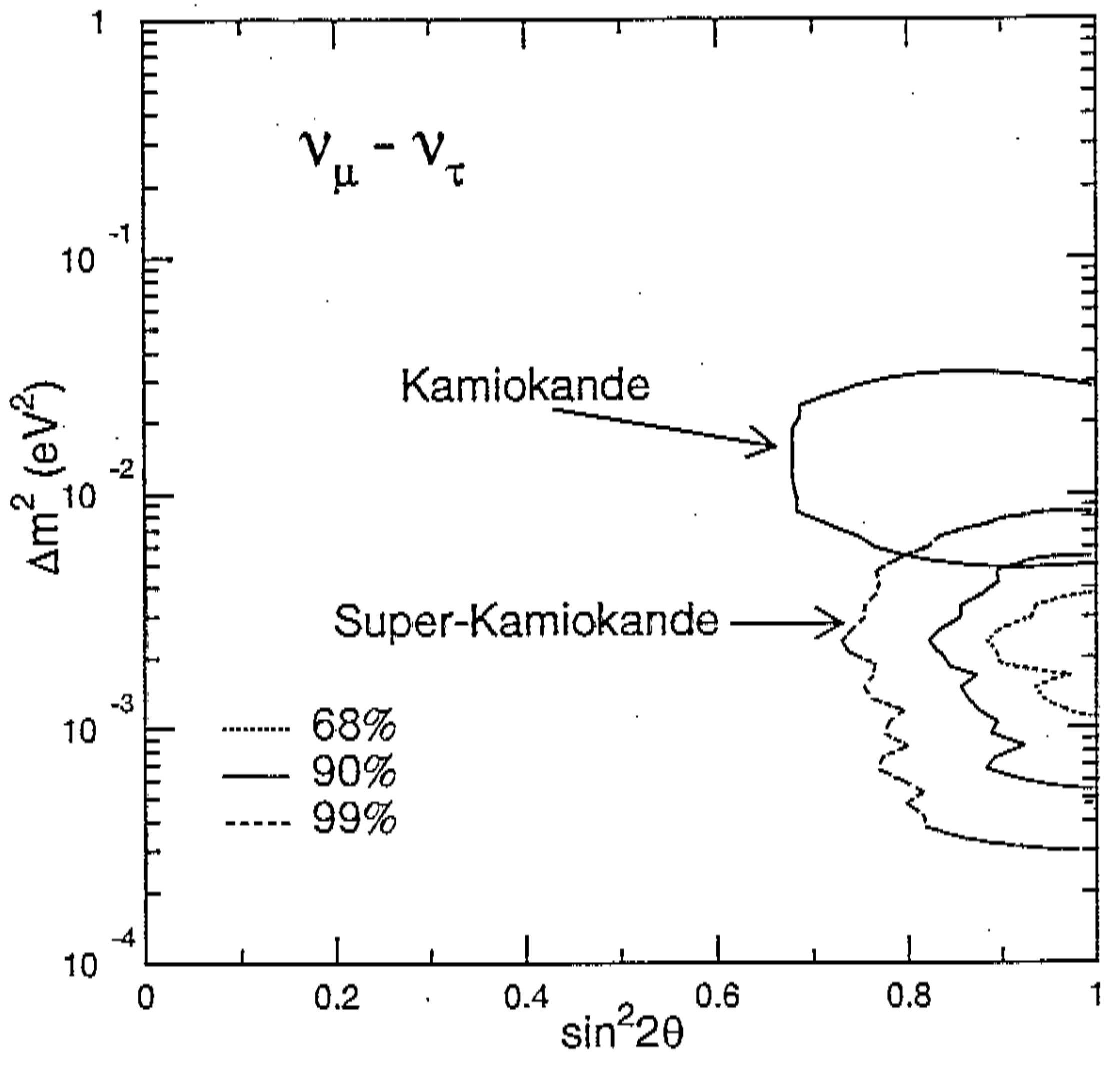
IS THIS OSCILLATION? PLOT RATE vs. L/E.



:::::: FITS TO OSCILLATION HYPOTHESIS ($\nu_\mu \leftrightarrow \nu_\tau$)

- PROBABLY NOT PREDOMINANTLY $\nu_\mu \leftrightarrow \nu_e$. (NO ν_e ENHANCEMENT)
- COULD BE $\nu_\mu \leftrightarrow \nu_\tau$. (FITS VERY WELL) – but can't observe ν_τ
- COULD ALSO BE $\nu_\mu \leftrightarrow \nu_?$ (NEW "STERILE" ν — MORE ON THIS LATER)

INTERPRETING AS $\nu_\mu - \nu_\tau$ OSCILLATION:

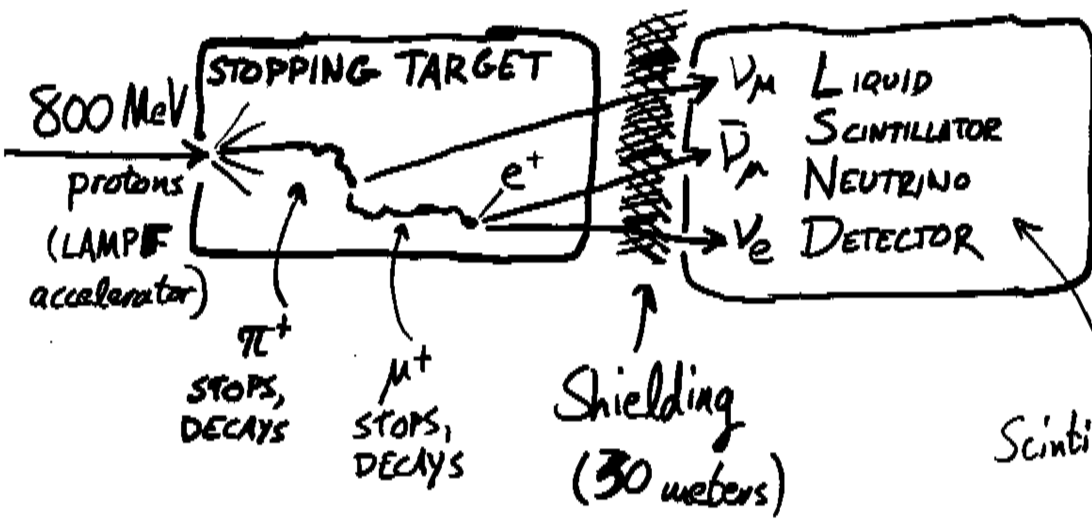


$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \, \sin^2\left[1.27\, \Delta m^2 \frac{L}{E}\right]$$

THE LSND "APPEARANCE" EFFECT

→ A SEARCH FOR $\bar{\nu}_\mu \to \bar{\nu}_e$ OSCILLATIONS.

NEUTRINO SOURCE: AT LOS ALAMOS NAT'L LAB.



NO $\bar{\nu}_e$ IN DECAY CHAIN!

SEARCHING FOR $\bar{\nu}_e$ APPEARANCE:

$L = 30$ meters; $E = 30-55$ MeV.

SIGNAL:

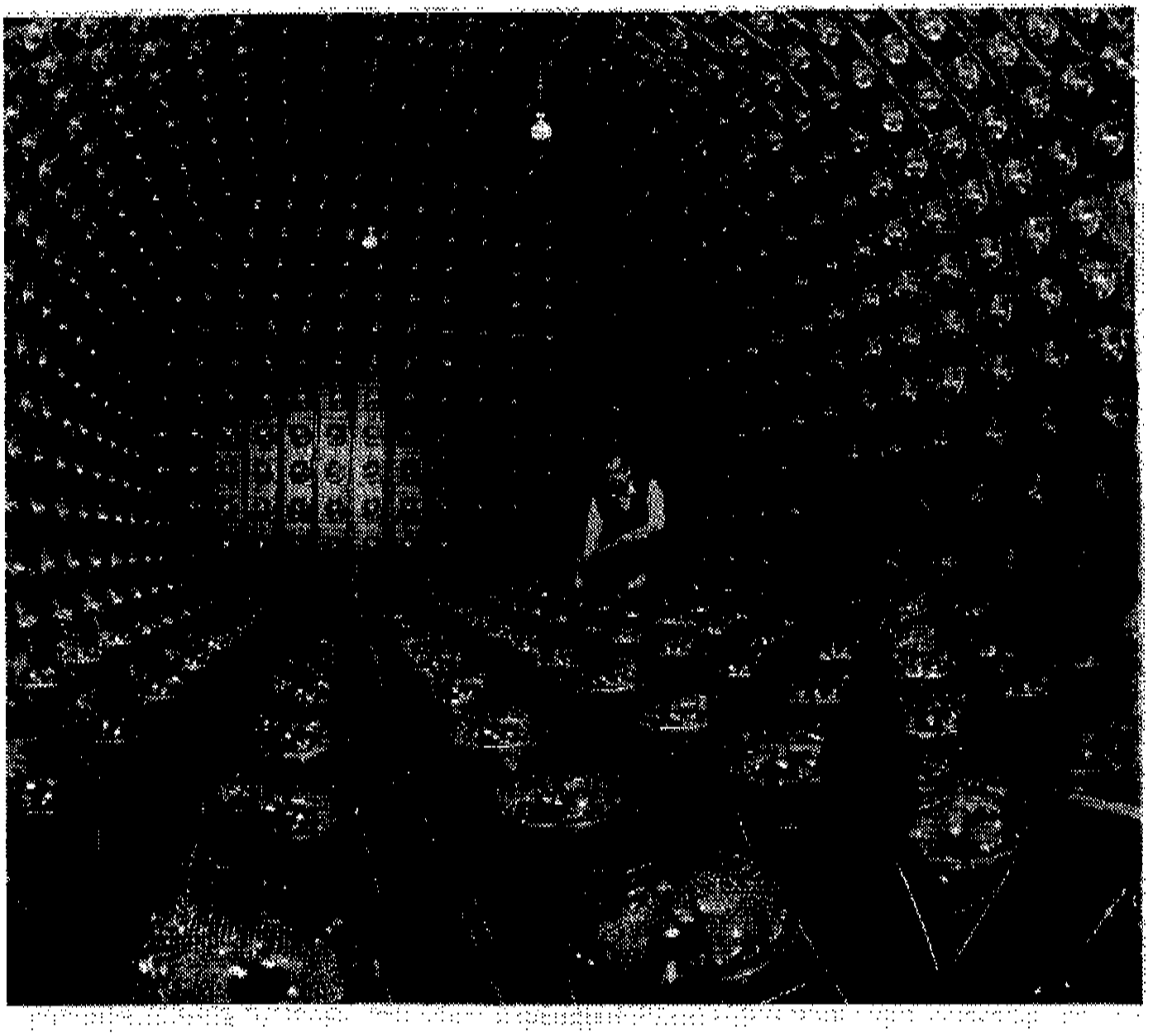
$\bar{\nu}_e$-^{12}C interaction produces e^+ and neutron in oil.

$e^+ \to$ prompt flash of light

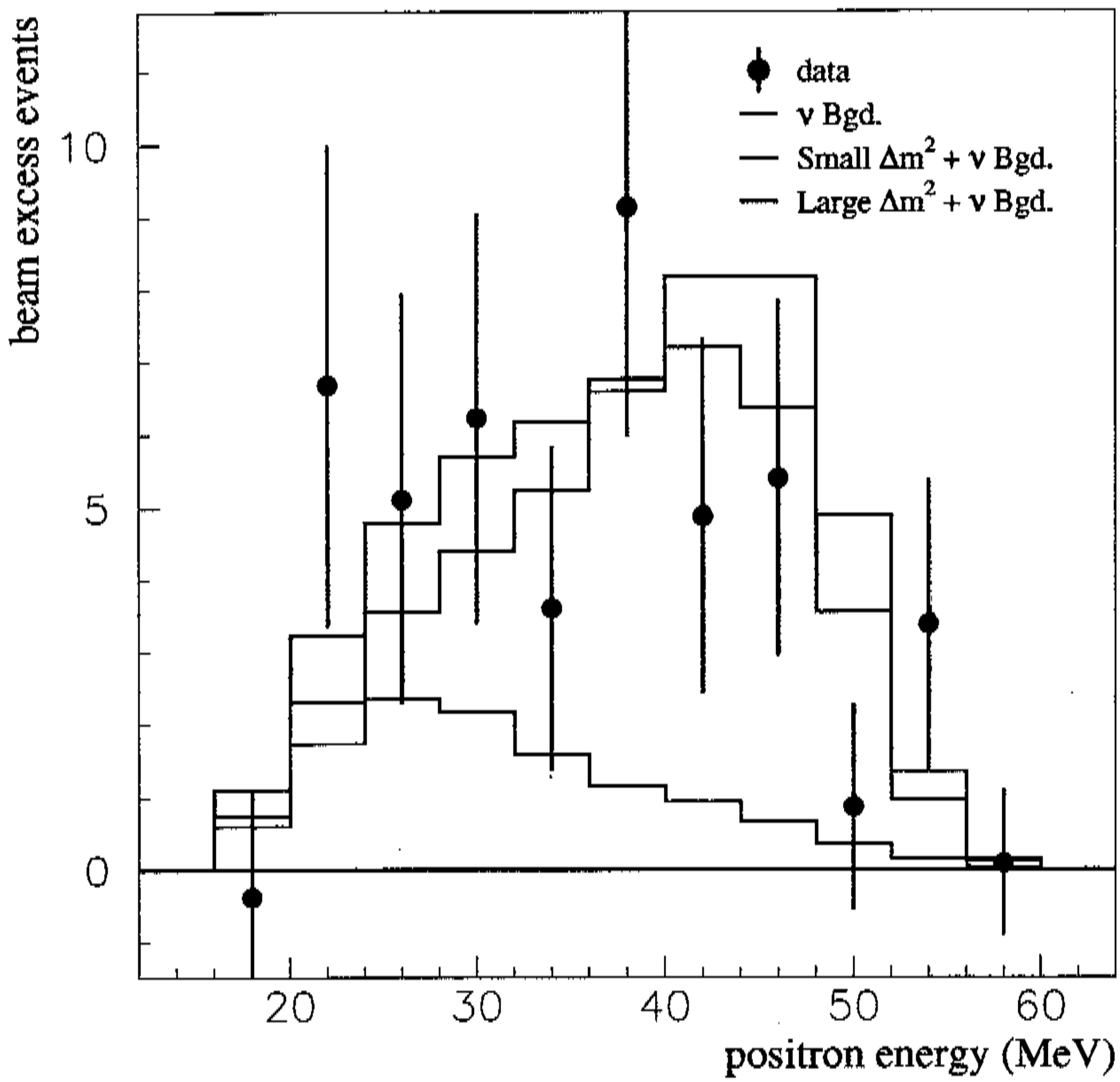
$n \to$ eventually captured to form $^2H + \gamma$ (2.2 MeV)

γ produces another flash

LOOK FOR DELAYED COINCIDENCE.



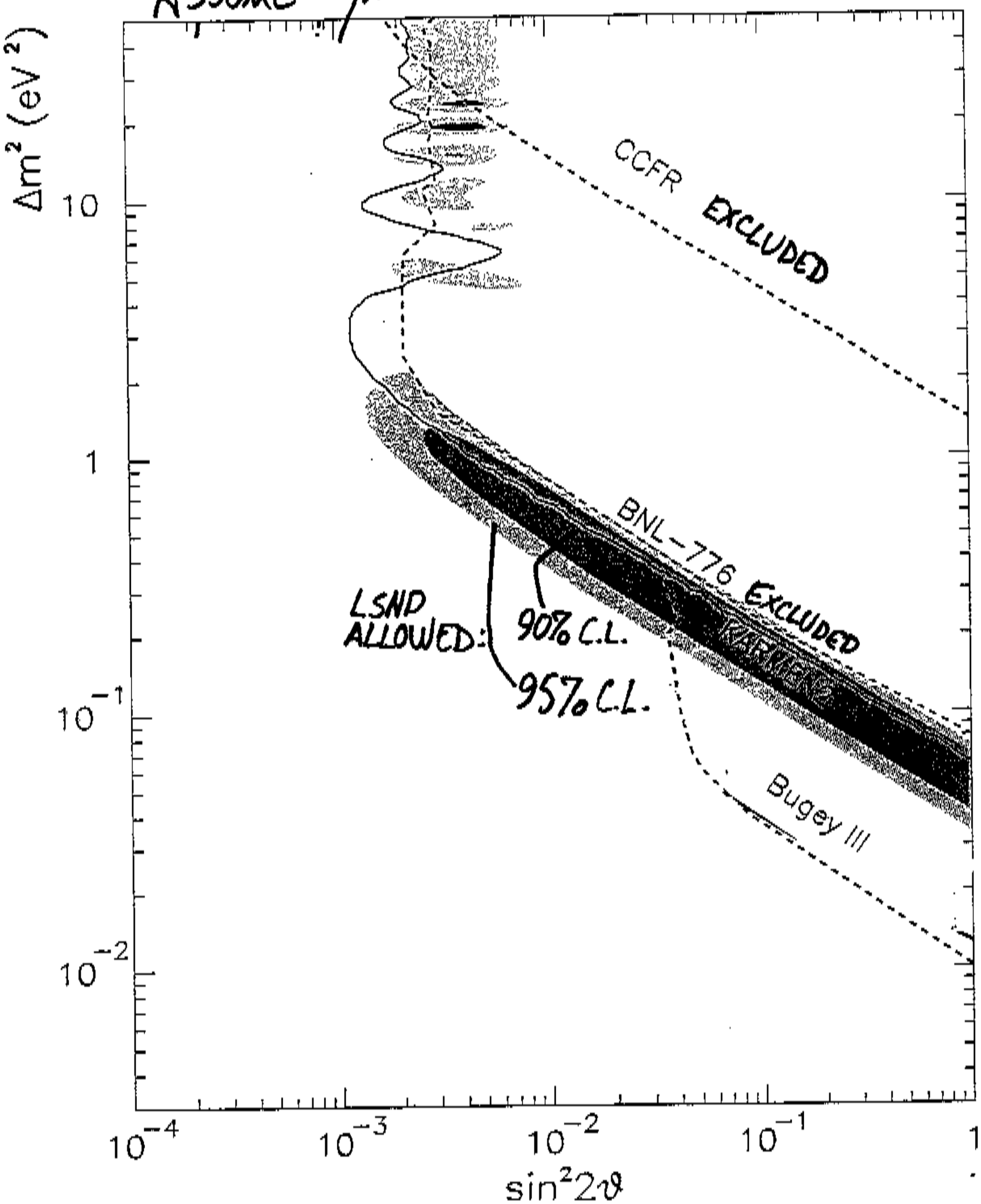
ν_e CANDIDATES
LSND DATA
1993-97
~4.5σ EXCESS OVER BACKGROUND



TRANSLATE TO OSCILLATION PARAMETERS...

LSND ALLOWED REGION

ASSUME $\nu_\mu - \nu_e$ MIXING DOMINATES EFFECT.



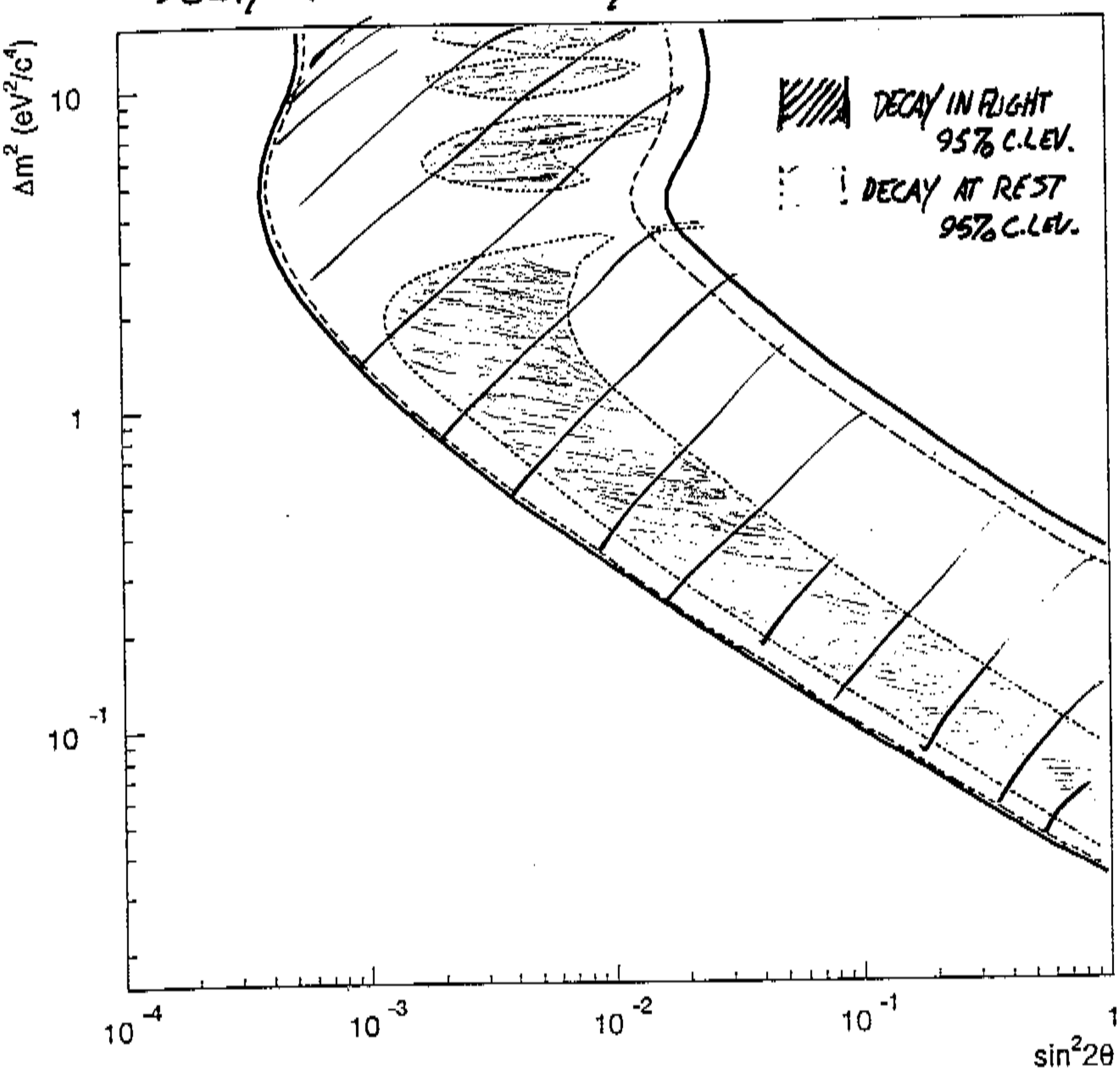
- KARMEN 2 = SIMILAR EXP'T IN ENGLAND; SMALLER L/E; SEES NO EVIDENCE FOR OSCILLATION

DECAY-IN-FLIGHT ANALYSIS:

AT LSND, SOME π^+ DECAY IN FLIGHT UPSTREAM OF THE STOPPING TARGET, PROVIDING HIGHER-ENERGY ν_μ.

ALLOWS AN INDEPENDENT $\nu_\mu \to \nu_e$ SEARCH WITH DIFFERENT SYSTEMATICS.

2σ ν_e EXCESS OBSERVED, CONSISTENT WITH MAIN "DECAY-AT-REST" ANALYSIS.



- # SOLAR NEUTRINOS

THE OLDEST "NEUTRINO PROBLEM"

(known for ~30 years)

- SEVERAL PROCESSES IN THE SUN PRODUCE LARGE NUMBERS OF ν_e.

- EXPERIMENTS DETECT THESE ν_e AND COMPARE TO THE "STANDARD SOLAR MODEL" PREDICTION.

E: 0.1 — 10 MeV

L: 1 ASTRONOMICAL UNIT

PROCESSES OBSERVED:

"Chlorine" experiments: Homestake

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

"Gallium" experiments: SAGE, Gallex

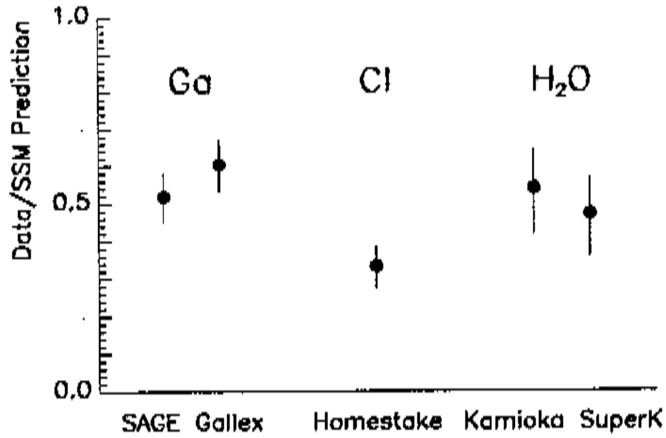
$$\nu_e + {}^{71}Ga \longrightarrow {}^{71}Ge + e^-$$

Water target e-ν scattering: Kamiokande, Super K

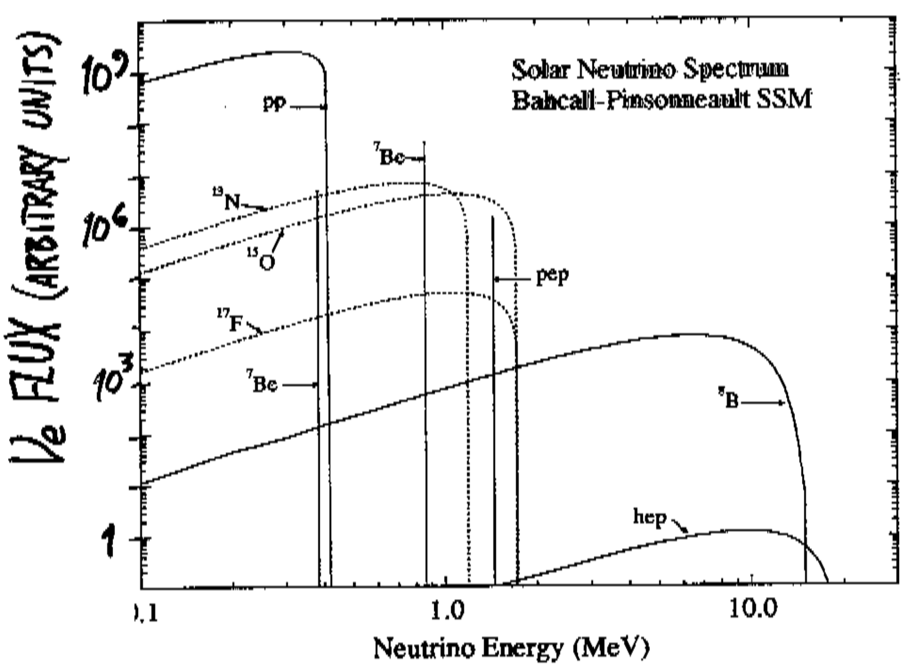
$$\nu_e + e^- \longrightarrow \nu_e + e^-$$

Comparing the results of these experiments to
"The Standard Solar Model (SSM)"...

... They see only $\sim 1/2$ the expected rate!

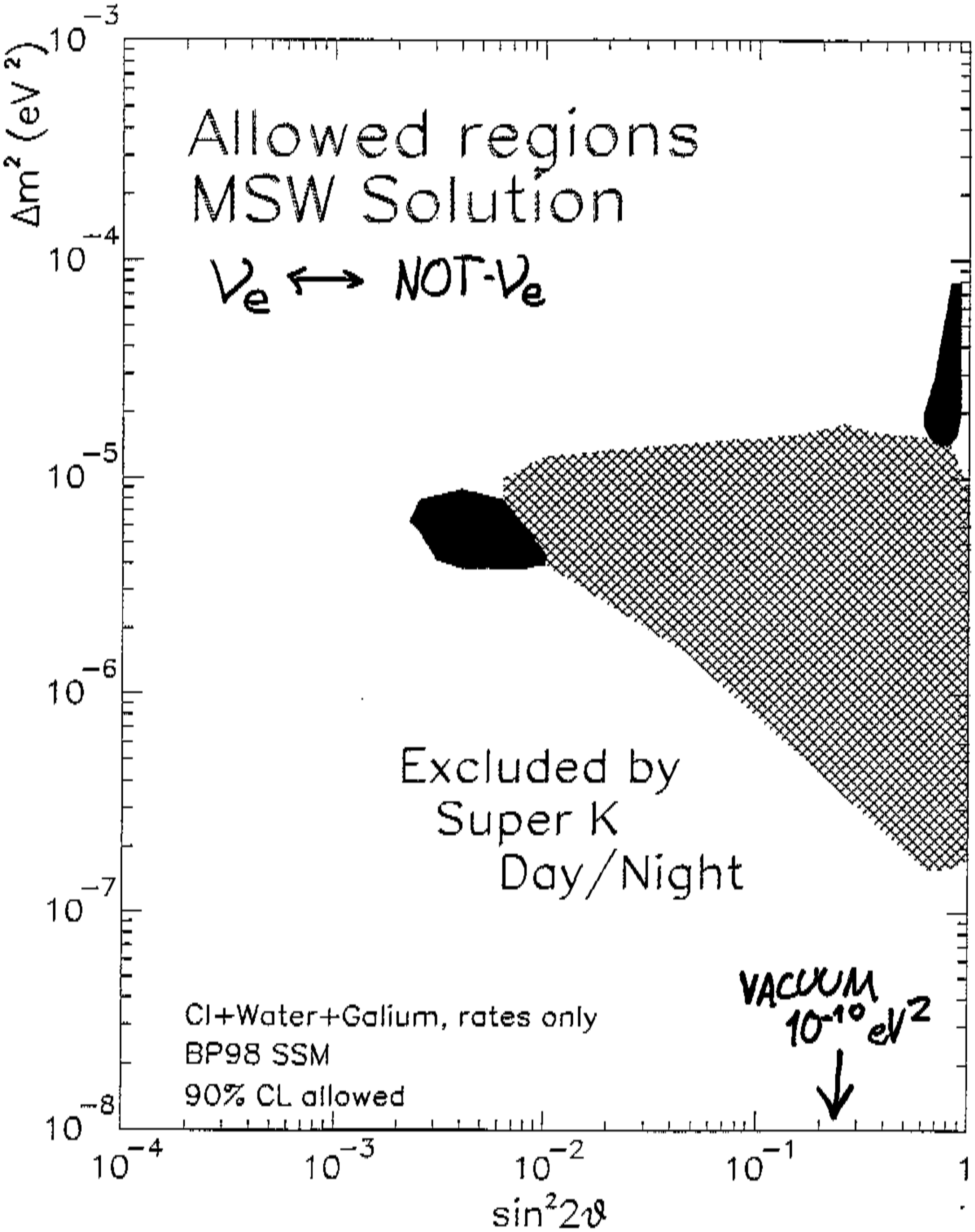


ν source	> 0.23 MeV	> 0.8 MeV	> 7.0 MeV
pp	51%		
^{7}Be	28%	13%	
pep	2%	2%	
CNO	7%	5%	
^{8}B	12%	80%	100%



OSCILLATION PARAMETERS FOR SOLAR ν:

"MSW" solutions rely on interference effects in matter to enhance oscillations.



With "vacuum oscillations", chlorine result can only be accommodated with others if $\Delta m^2 \sim 10^{-10}$ eV^2 ("Just-So" solution)

NEUTRINO OSCILLATION:

THE EXPERIMENTAL PICTURE IS VERY CONFUSING.

LSND: $\Delta m^2 > 0.1\ eV^2$ $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$

ATMOSPHERIC: $\Delta m^2 \approx 2 \times 10^{-3}\ eV^2$ $\nu_\mu \leftrightarrow ?$

SOLAR: $\Delta m^2 < 10^{-4}\ eV^2$ $\nu_e \leftrightarrow ?$

With only 3 ν masses, you can't construct 3 Δm^2 values with different orders of magnitude.

Is there a fourth neutrino?

If so, it can't interact weakly, because it would contribute to the decay width of the Z^0. (this is measured to be consistent with only 3 ν's.)

WE NEED:
- A "STERILE" FOURTH ν (THEORETICALLY UNMOTIVATED)

OR
- ONE OF THE OBSERVED EFFECTS IS NOT OSCILLATIONS

OR
- A NEW IDEA

NEXT STEP: ATMOSPHERIC ν PROBLEM

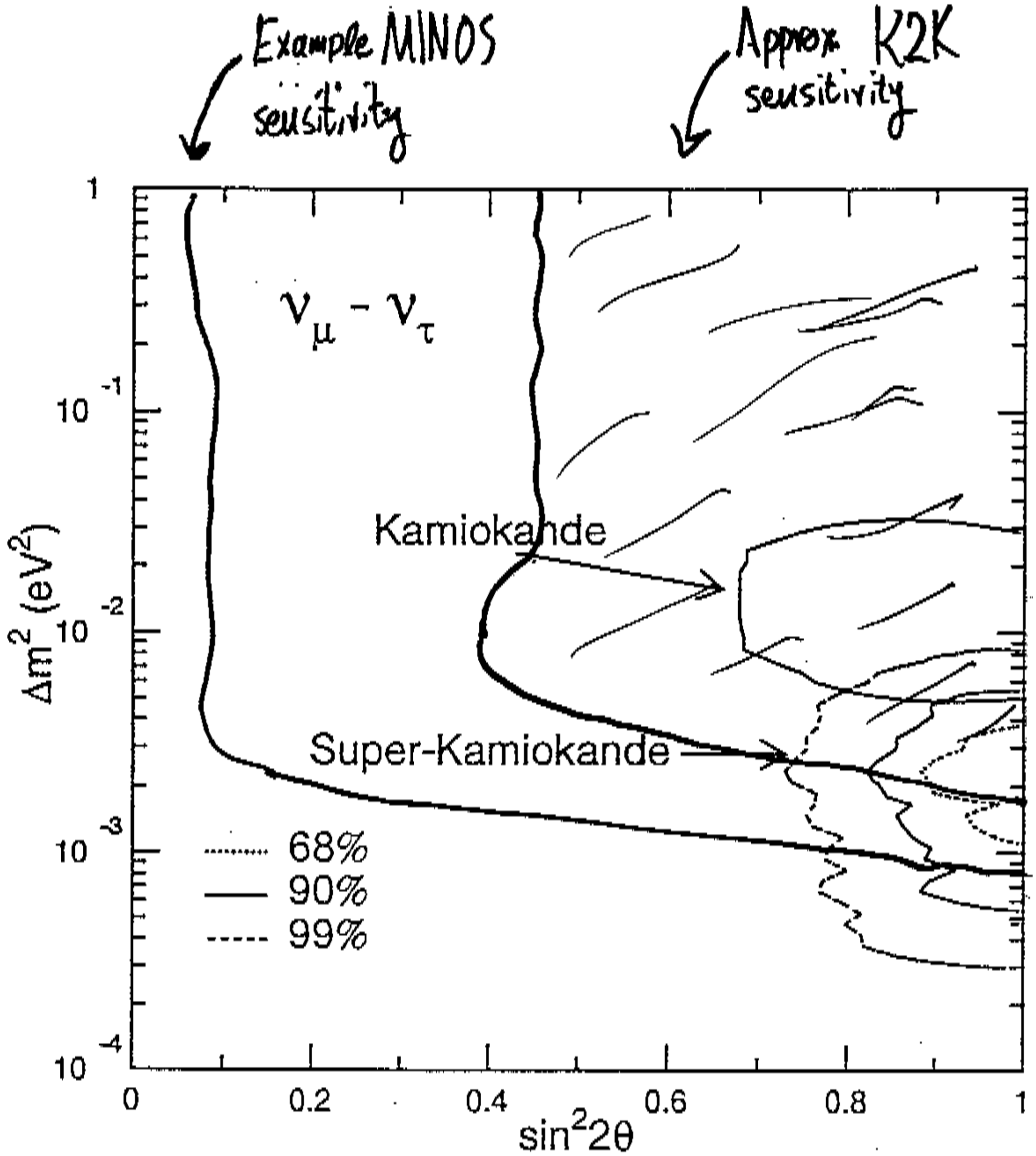
LONG BASELINE ACCELERATOR EXPERIMENTS —

- CREATE A ν BEAM
- AIM THROUGH ~HUNDREDS OF km OF EARTH AT A NEUTRINO DETECTOR
- PLACE SECOND DETECTOR NEAR ν SOURCE TO MEASURE INITIAL FLUX
- USE FAR DETECTOR TO MEASURE "OSCILLATED" FLUX

→ BETTER BEAM CONTROL, PURITY

→ LOWER SYSTEMATIC ERRORS

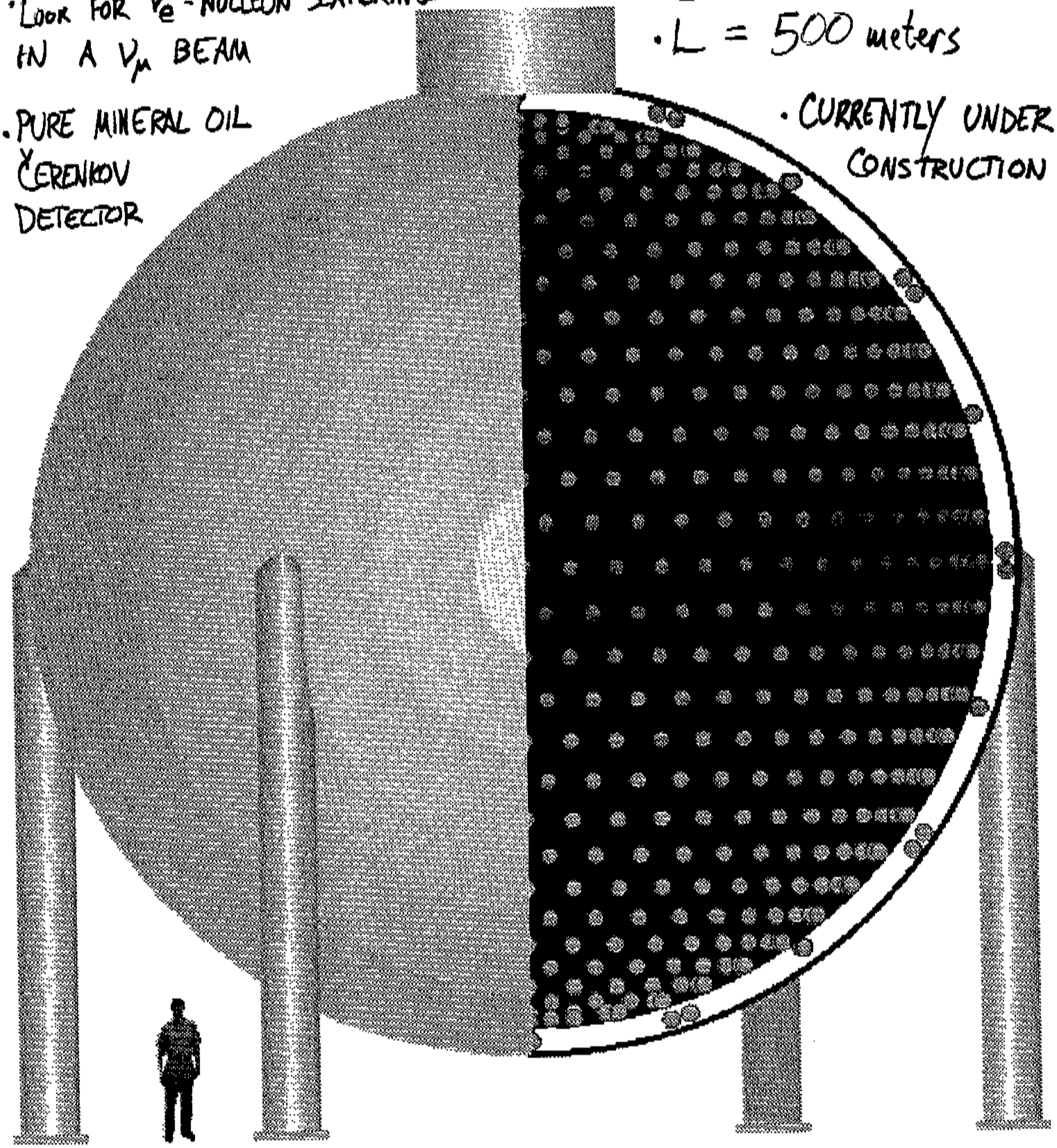
"K2K" (KEK TO KAMIOKA)	MINOS
• BEAM FROM KEK SYNCHROTRON TO SUPERKAMIOKANDE DETECTOR	• BEAM FROM FERMILAB (ILLINOIS) TO SOUDAN MINE (MINNESOTA)
• $E \sim 3$ GeV	• $E = 3 \rightarrow 20$ GeV (variable)
• $L \sim 250$ km	• $L \sim 730$ km
• Running 1999–?	• Scheduled run 2003-4
• VERY PRELIMINARY $\sim 2\sigma$ EVIDENCE FOR ν_μ DISAPPEARANCE	



VERY APPROXIMATE SENSITIVITY OF LONG-BASELINE ACCELERATOR EXPERIMENTS

NEXT STEP ON LSND EFFECT: $\boxed{\text{MINI-BOONE}}$ AT FERMILAB

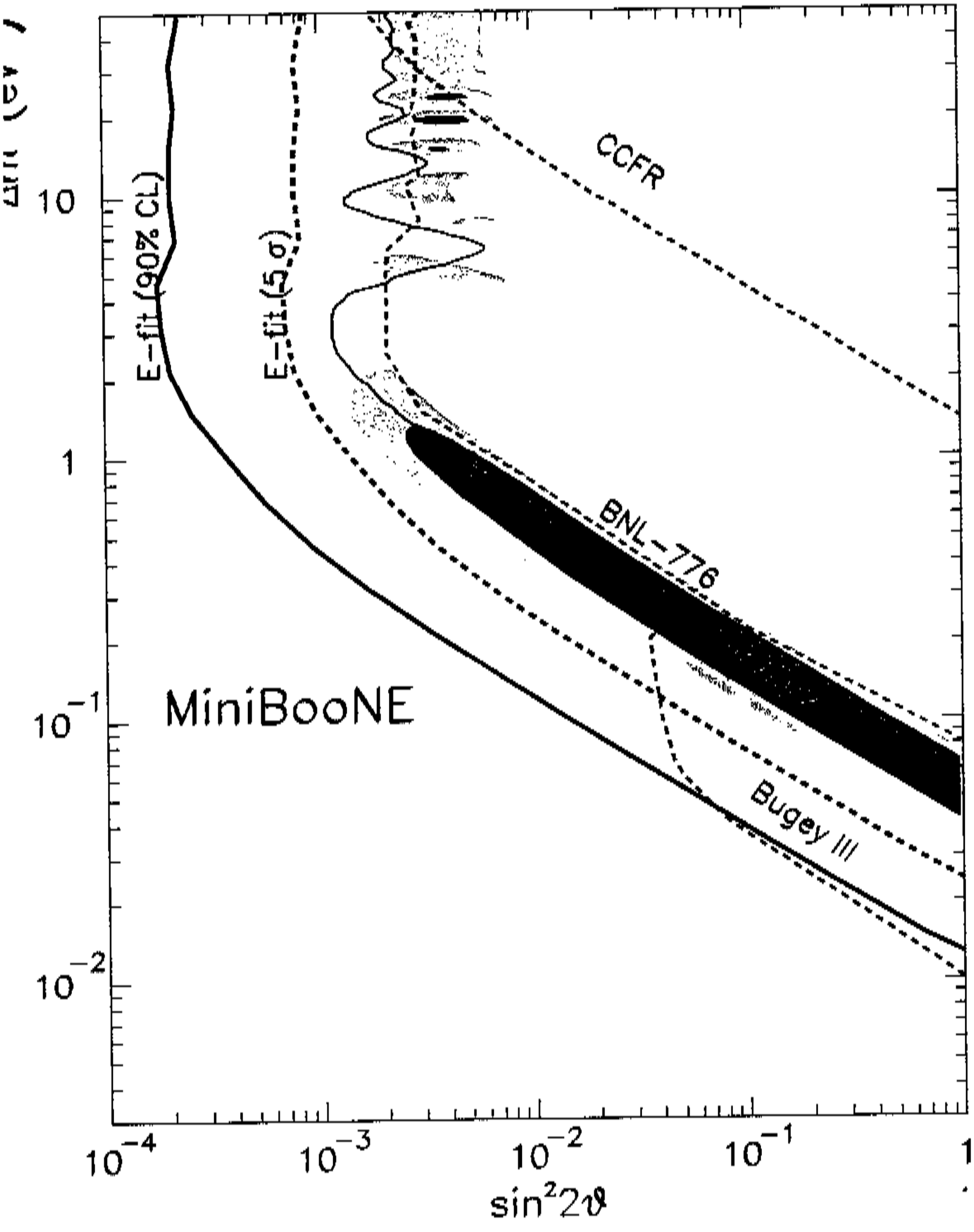
- LOOK FOR ν_e - NUCLEON SCATTERING IN A ν_μ BEAM
- PURE MINERAL OIL ČERENKOV DETECTOR
- $E = 0.2 - 1.0$ GeV
- $L = 500$ meters
- CURRENTLY UNDER CONSTRUCTION



GETTING READY TO TAKE DATA AT END OF 2001.

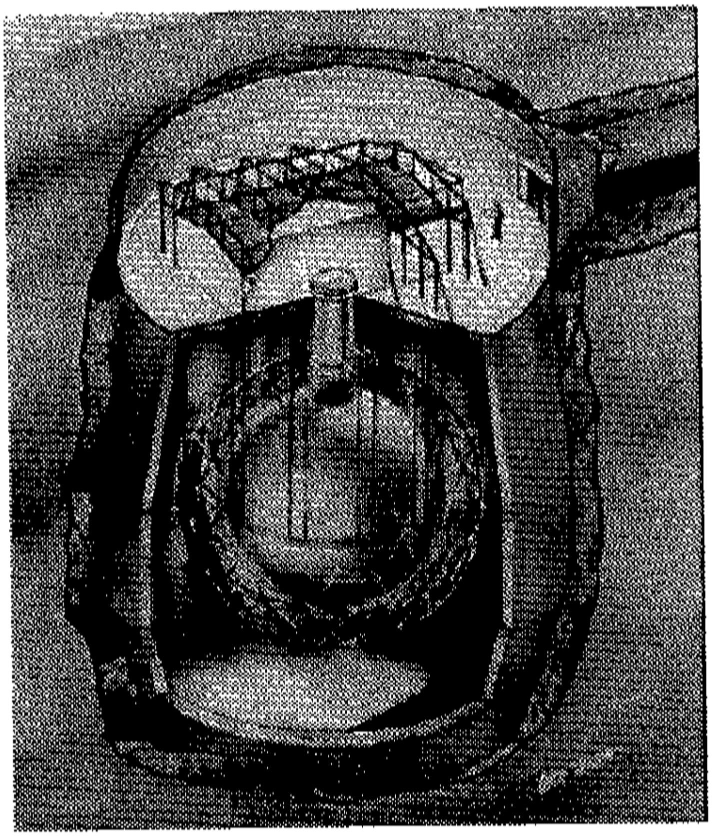
MINI-BOONE: EXPECTED SENSITIVITY

- DEFINITIVELY CONFIRM OR RULE OUT LSND EFFECT AS DUE TO NEUTRINO OSCILLATIONS.



(NUMBERS FOR 1-YEAR RUN)

SUDBURY NEUTRINO OBSERVATORY (SNO)



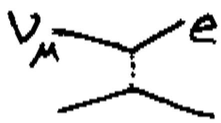
NEXT BIG STEP ON SOLAR NEUTRINO PROBLEM

SNO will distinguish

$\nu_e \rightarrow \nu_{\mu,\tau}$ FROM $\nu_e \rightarrow \nu_{STERILE}$.

RUNNING SINCE 1999

FIRST REAL SEARCH FOR NEUTRAL CURRENT INTERACTIONS FROM SOLAR NEUTRINOS: DEUTERON DISSOCIATION IN HEAVY WATER TARGET. $\nu + {}^2H \rightarrow p + n + \nu$

PREDICTION UNDER $\nu_e \rightarrow \nu_\mu$ OR ν_τ HYPOTHESIS	PREDICTION UNDER $\nu_e \rightarrow \nu_{STERILE}$ HYPOTHESIS
ν_e CHARGED CURRENT: DEFICIT — LIKE OTHER EXPTS  ~50% of ν_e OSCILLATED $\rightarrow \nu_{\mu,\tau}$	ν_e CHARGED CURRENT: DEFICIT — LIKE OTHER EXPTS
$\nu_{\mu,\tau}$ CHARGED CURRENT: NO EVENTS — NOT ENOUGH ENERGY TO CREATE μ OR τ	NEUTRAL CURRENT: STERILE ν HAS NO INTERACTION AT ALL — SO DEFICIT HERE TOO.
$\nu_{e,\mu,\tau}$ NEUTRAL CURRENT: ALL THREE SPECIES CONTRIBUTE — SO RATE SHOULD MATCH STANDARD SOLAR MODEL	

CONCLUSIONS:

WE DON'T KNOW...

- HOW MANY NEUTRINOS THERE ARE
- HOW THEY MIX (IS THERE CP VIOLATION?)
- WHAT THEY WEIGH (EVEN TO ORDERS OF MAGNITUDE!)
- IF THEY HAVE NONSTANDARD INTERACTIONS
- IF THEY HAVE DISTINGUISHABLE ANTIPARTICLES

... BUT WE HAVE TANTALIZING HINTS AND POWERFUL NEW EXPERIMENTS WHICH WILL TEST KEY NOTIONS.

THIS IS ABOUT WHERE WE WERE UNDERSTANDING QUARKS 25 YEARS AGO.

THERE WILL BE MAJOR DISCOVERIES SOON.

IT'S AN EXTREMELY EXCITING TIME.