Neutrinos

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COE Symposium
Sendai
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- History of development of ideas & experiments on neutrinos
- Current status of knowledge of neutrino properties
- Plans for near future
- Neutrino Cosmology
  - Detection of Relic Neutrinos
- Uses of Neutrino Telescopes
- Applications of Neutrinos
  - Earth Exploration (oil?)
  - Geophysics
  - Disarmament - Arms Control (Very far future).

A NEUTRINO TIMELINE

The following is a short history of neutrinos as it relates to neutrino oscillation studies.

1920-1927 Charles Drummond Ellis (along with James Chadwick and colleagues) establishes clearly that the beta decay spectrum is really continuous, ending all controversies.

1930 Wolfgang Pauli hypothesizes the existence of neutrinos to account for the beta decay energy conservation crisis.

1932 James Chadwick discovers the neutron.

1933 Enrico Fermi writes down the correct theory for beta decay, incorporating the neutrino.
1938 Hans Bethe, C.F. von Weizacker propose PP cycle for solar energy.
1946 Shoichi Sakata and Takesi Inoue propose the pi-mu scheme with a neutrino to accompany muon.
Bruno Pontecorvo suggests $Cl \to Ar$ as ν_e detector
1956 Fred Reines and Clyde Cowan discover (electron anti-) neutrinos using a nuclear reactor.

1957 Neutrinos found to be left handed by Goldhaber, Grodzins and Sunyar.

1957 Bruno Pontecorvo proposes neutrino-antineutrino oscillations analogously to K0-K0bar, this is the first time neutrino oscillations (of some sort) are hypothesized.

1962 Ziro Maki, Masami Nakagawa and Sakata introduce neutrino flavor mixing and flavor oscillations.

1962 Muon neutrinos are discovered by Leon Lederman, Mel Schwartz, Jack Steinberger and colleagues at Brookhaven National Laboratories and it is confirmed that they are different from electron neutrinos.

1964 John Bahcall and Ray Davis discuss the feasibility of measuring neutrinos from the sun.

1965 The first natural neutrinos are observed by Reines and colleagues in a gold mine in South Africa, and by Goku Menon and colleagues in Kolar gold fields in India, setting first astrophysical limits.

1968 Ray Davis and colleagues get first radiochemical solar neutrino results using cleaning fluid in the Homestake Mine in North Dakota, leading to the observed deficit now known as the "solar neutrino problem". (with accompanying paper by John Bahcall).

1976 The tau lepton is discovered by Martin Perl and colleagues at SLAC in Stanford, California. After several years, analysis of tau decay modes leads to the conclusion that tau is accompanied by its own neutrino, nutau, which is neither nue nor numu.

1980s The IMB, the first massive underground nucleon decay search instrument and neutrino detector is built in a 2000' deep Morton Salt mine near Cleveland, Ohio. The Kamioka experiment is built in a zinc mine in Japan (led by Masatoshi Koshiba).

1985 The "atmospheric neutrino anomaly" is observed by IMB and Kamiokande.

1986 Kamiokande group makes first directional counting observation solar of solar neutrinos and confirms deficit.

1987 The Kamiokande and IMB experiments detect burst of neutrinos from Supernova 1987A, heralding the birth of neutrino astronomy, and setting many limits on neutrino properties, such as mass.

1988 Lederman, Schwartz and Steinberger awarded the Physics Nobel Prize for the discovery of the muon neutrino.

1989 The LEP accelerator experiments in Switzerland and the SLC at SLAC (Stanford) determine that there are only 3 light neutrino species (electron, muon and tau).

1991-2 SAGE (in Russia) and GALLEX (in Italy) confirm the solar neutrino deficit in radiochemical experiments.

1995 Frederick Reines and Martin Perl share the Physics Nobel Prize for discovery of electron neutrinos (and observation of supernove neutrinos) and the tau lepton, respectively.

1996 Super-Kamiokande, the largest particle detector ever, begins searching for neutrino interactions on 1 April at the site of the Kamioka experiment, with a Japan-US team(led by Yoji Totsuka).

1998 After analyzing more than 500 days of data, the Super-Kamiokande team reports finding oscillations in atmospheric neutrinos and, thus, neutrino mass.

1999-2000 The Chooz and Palo Verde reactor experiments report no oscillations, concluding that electron neutrinos are not the dominant participant in the atmospheric neutrino oscillations.

2000 The DONUT Collaboration working at Fermilab announces observation of tau particles produced by tau neutrinos, making the first direct observation of the tau neutrino.

2000 Super-Kamiokande announces that the oscillating partner to the muon neutrino is not a sterile neutrino, but the tau neutrino.

2001-02 SNO announces observation of neutral currents from solar neutrinos, along with charged currents and elastic scatters, providing convincing evidence that neutrino oscillations are the cause of the solar neutrino problem.(led by Art McDonald).

2002 Masatoshi Koshiba and Raymond Davis win Nobel Prize for measuring solar neutrinos (as well as supernova neutrinos).

2002 KamLAND observes neutrino oscillations consistent with the solar neutrino puzzle using, for the first time, man-made neutrinos(led by Atsuto Suzaki).

Modified by Giorgio Gratta from an original by John Leaned and Sandip Pakvasa.

This page is maintained by jasondet@stanford.edu.

Nov. 1895 Röntgen discovered X-rays
(from CRT walls)

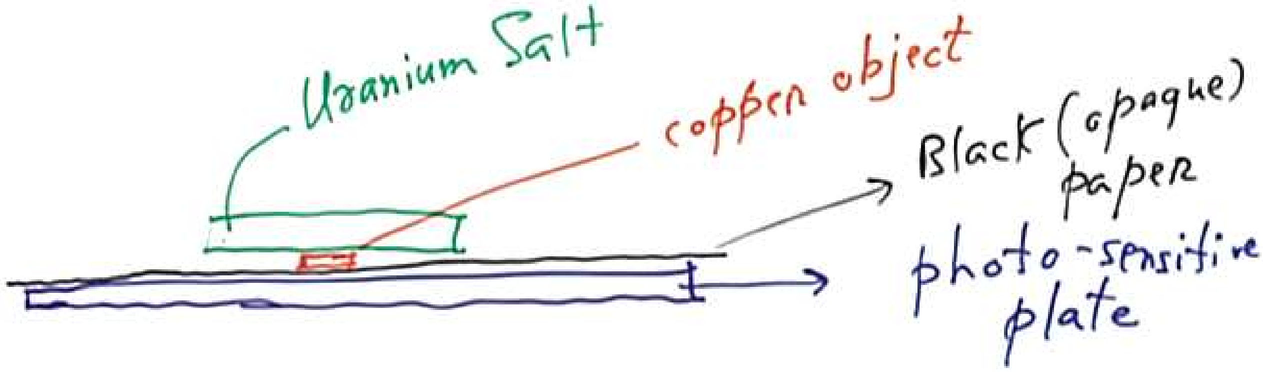
Jan. 1 1896 Henri Becquerel hears about X-rays from a lecture by Poincaré.
→ Starts experiments

Thinks some flourescent materials also might emit X-rays. Uses Uranium to try to expose photo. plates.
Scheduled to give a talk on mar. 1.
Impatient for results, develops plates (wrapped in black paper) inside a drawer on Feb 25 & finds them blackened (it was a cloudy day).

Feb. 25, 1896 H.B. discovers "radioactivity" (so named 4 years later by Marie Curie)

1898 Ernest Rutherford (Cambridge) & P. & M. Curie start work on radioactivity.

Becquerel's Apparatus (S. Thompson in U.K.)



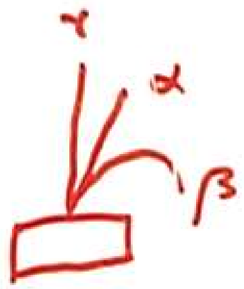
- Initially exposed to sunlight & then developed.

  found darkened paper except where object (cross) placed.

- Left over a weekend inside a drawer (no sunlight). Developed on sunday — results identical!
- Delivered a talk on monday.
- Established
  - It is the Uranium
  - ~~Rad~~ is Ionising - - -

Rutherford : . found exponential decay law.

. found . penetrating radiation
(he called it β-rays)



. "stoppable" radiation
(called it α-rays)

. applied B field
. found β-rays deflected
$\Longrightarrow$ charged particles

(finally in 1903 found
α-rays deflected in
strong enuf B).

{rays undeflected
→ γ-rays}

M. & P. Curie : . found α-rays can be slowed down in matter, hence heavy material particle

. discovered other stronger radioactive elements without which further detailed experiments impossible. Th, Ra, Po.

Nature of β-spectra in radioactive nuclei?

"Life & Times of C. D. Ellis" (Pais)

- Very rich & hence complicated & situation confused.
- 1912 – 1914. James Chadwick switched to counter technique (from emulsion) with β & began to get some clarity.
- lines + Continuum.
  ↳ understood later as Auger transitions
- 1915 Rutherford lecture mentions continous spectrum & that each decay may give diff. energy to β.
- 1914 Chadwick accepts a Royal Scholarship to work in Berlin. & is interned, allowed to continue research in "prison" & meets Charles Drummond Ellis, an artillery officer.

1919 Ellis gives up army & follows Chadwick to Cambridge

→ start of a "beautiful" collaboration

"Work of Ellis et al. in 20's primarily responsible for those experimental advances which were to lead to the neutrino hypothesis" (A. Pais).

1921. Ellis clarified:

(i) some β's are <u>secondaries</u> via <u>internal conversion</u> of <u>primary</u> γ-rays.
└ (first observ.)

(ii) confirmed Einstein photo-electron formula at MeV scale (6 orders of magnitude improvement).

1922 (paper #2). · First sketch of a nuclear energy level diagram

· First suggestion that Q. Theory applicable to nuclei.

Ellis & Chadwick thought:

- β-spectra clarified
  - → primary spectra continuous
  - lines from secondary spectra

<u>But 1922-3</u> → L. Meitner claims

- primary spectra discrete
- they may have full energy or less & give γ-rays → secondary β's

She claimed experimental evidence for her "model" (which is analogous to α-decay spectra).

Long controversy ensued back & forth. (In 1925 Compton effect was found & Meitner tried to use it to "explain" continuum, Ellis & Chadwick said "no way").

Compton results first direct test of energy-momentum conservation in elementary processes.

1925: Ellis & Wooster reviewed all arguments, conclude "there is no doubt ... that this (continuum) exists...." but decided to settle it the only way possible: experimentally.

· To Do an old fashioned, fully calorimetric determination of total emitted energy. (by registering temp. rise).

$$\langle \Delta T \rangle = \begin{cases} E_{max} & \text{(Meitner)} \\ \langle E_e \rangle & \text{Ellis-Chadwick} \end{cases}$$

· It took 2 years. Result. (1927).

The spectrum is Continous.

· "Great shock" to Meitner. But as the good physicist she repeated the experiment & published results in Dec. 1929. Agreement!

1929 → Bohr - Pauli Controversey

1924 - 1936 Bohr advocated violation of energy conservation to explain continous β-spectrum.

Several Serious Crises

① · Continous β-ray spectrum

$$(N, Z) \longrightarrow (Z+1) + e^-$$

② · presence of electrons in nuclei creating problems with spin & statistics

③ · problems with Dirac Eq. & Klein Paradox.

p.s. Eventually all solved by NEW PARTICLES!!

① → neutrino, ② → neutron (Chadwick 1932)

③ → positron (Anderson 1932)

1924: Bohr- Kramers- Slater paper (stat. cons. of E)
BUT 1925 → Compton

Problem of Nuclear Statistics

e.g. ^{14}N: mass ~ 14 m_p

⇒ must contain 14 protons

charge ~ +(7e)

⇒ must contain 7 electrons

$\{[+14-7] = +7\}$

Hence ^{14}N nuclei should obey Pauli principle & Fermi statistics.

But molecular Spectra of ^{14}N (Diatomic) Molecules showed they obeyed Bose Statistics

Also Spin of ^{14}N not ½ integer but integer (in $\hbar$)

Pauli insisted on energy, momentum, angular momentum conservation.

The famous Pauli letter: (next transp.

The reasons why Pauli never published, was reticent and reluctant:

- general conservatism.
- more importantly, Pauli was trying to solve two problems
  - (i) β-ray spectrum
  - (ii) spin & statistis in nuclei

& this led to serious contradictions

(a) (i) implied $m_\nu \sim$ small $\leq m_e$

(b) For (ii) ν had to have "strong" binding forces (Pauli proposed "ν" should anom. magnetic moment). But then would leave tracks in cloud chambers "pictures would be teeming with "neutrons" "...

→ so Pauli did not really beleive in his invention (half right!)

Pauli's letter

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen these neutrons much earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think about this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant, W. Pauli

Pauli: (^{14}N) not $14p + 7e^-$ but $14p + 7e^- + 7\nu$

NOT $7P + 7N$.

1932-33

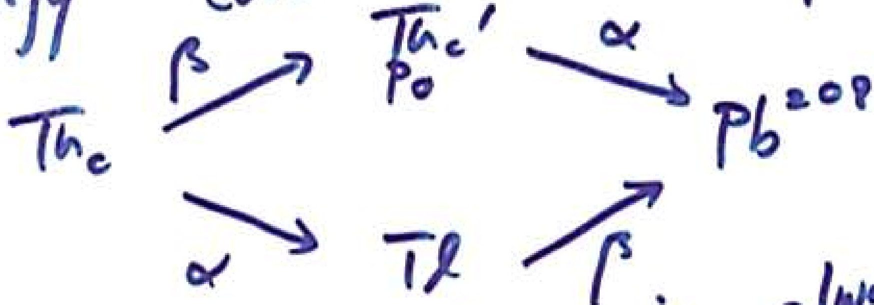
· 1932 Chadwick's discovery of the neutron (near miss by J-Curie)

· 1932 Anderson's discovery of the positron.

Things are getting clearer.

Oct. 1933 7th Solvay Conference.

Ellis reports on an Ellis-Mott expt. which beautifully confirms energy conservation in β-decay.



The sum of energies is always the same in both branches assuming

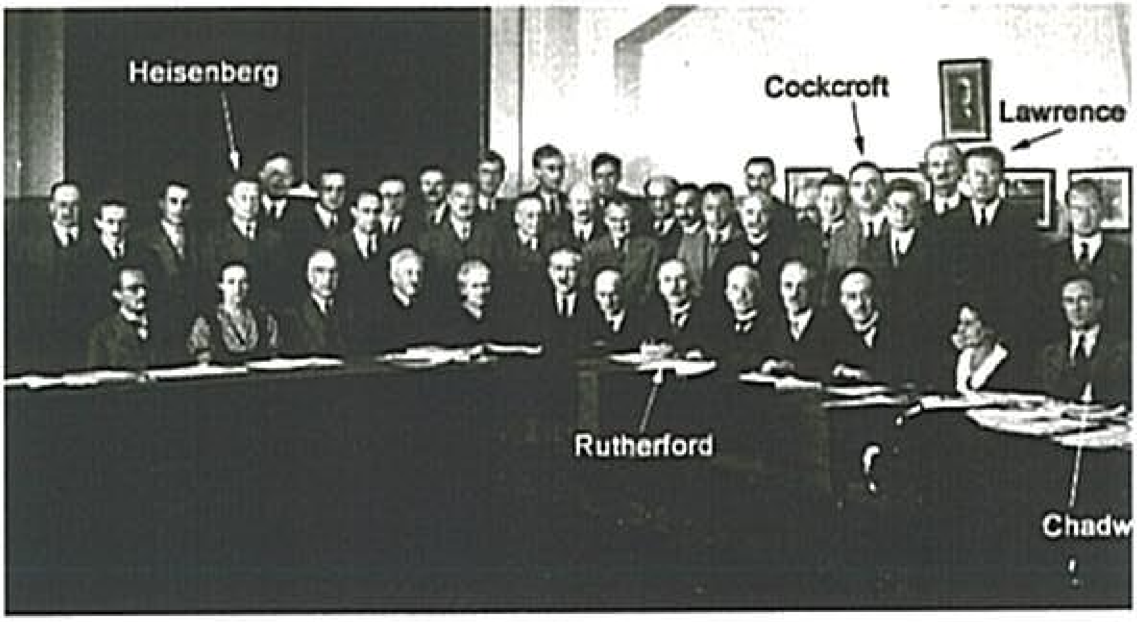
$\Delta M = E^{\beta}_{max}$.

Pauli discussed the neutrino

Perrin concludes that kinematics suggest $m_\nu \sim 0$.

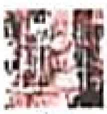
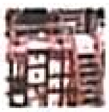
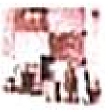
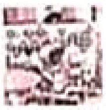
Fermi is present but silent.

Ernest Lawrence and the Cyclotron



Participants at the seventh Solvay Conference on nuclear physics, held in Brussels, Belgium in October 1933.

RETURN

 home
 youth and early career
 first cyclotron
 the Rad Lab
 big science
 the bomb
 cold war science
 the cold war
 more info

Dec. 1933 Fermi submits to Nature:
Tentativo di una teoria della emissione di raggi β
Nature: "speculations too remote from reality to be of interest to the reader"!
published in Nuov. Cim. & Z. für Phys.
1934: more detailed paper.

Digression: de Broglie (1934)
applied Dirac Eq. to neutrinos & called the hole in the Dirac sea as "anti-neutrino"
also for the first time coined the word "anti-particle"

Fermi was the first one to use quantized field for spin ½ in physics. (the use in QED by Heisenberg et al. was later!)

What's in Fermi's paper?

- the elementary process in β-decay is identified as the decay of neutron into peν. :

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

- Use analogy to QED to write the form of interaction

$$j_\mu A_\mu$$

$: j_\mu \sim \bar{\psi}_p \gamma_\mu \psi_n$

$: A_\mu \sim \bar{\psi}_\nu \gamma_\mu \psi_e$

→ in 1957, after p.v. only change to Fermi was $\gamma_\mu \to \gamma_\mu(1+\gamma_5)$

- Took NR limit (static)

$$j_\mu A_\mu \longrightarrow \rho \phi$$

$\rho \sim g_V \delta(\underline{x} - \underline{x}_0)$ position of neutron

$$\mathcal{H}_{int} \sim g_V \left[\tau_+ \bar{\psi}_\nu \gamma_0 \psi_e + \tau_- \bar{\psi}_e \gamma_0 \psi_\nu \right]$$

τ_+ & τ_- had just been introduced by Heisenberg (1932) !!

- β-spectrum calculated, dependence of end point behaviour on neutrino mass noted & small mass from data noted
- Concept of allowed & forbidden transitions introduced.

  $M_{pn} \sim \int \phi_p^* \phi_n \rightarrow 1$ or 0 etc

- estimated g_V (Fermi Coupling).

  $\sim 4 \cdot 10^{-50}$ erg-cc.

  $\rightarrow 1.4 \cdot 10^{-49}$ (today)

- July 1934 (Wolfe, Uhlenbeck) made an estimate of neutron lifetime from best p-n mass diff. & found 1000 sec. ("improbably small but no evidence to the contrary").
- Predictions of Fermi gave too few low energy β's. Kon. & Uhl. (1935) introduced derivatives to account for this, & fit the data perfectly.

Turned out these data were <u>wrong</u>!!
Back scattering problem → thinner sources
agreement perfect! "End of K & U!"

Meanwhile, Yukawa in Japan (1934) proposed "meson" (π) as a carrier of nuclear forces

- Yukawa Potential $V \sim e^{-\mu r}/r$

- Range $\sim \frac{1}{\mu} \sim \frac{\hbar}{m_\pi c} \sim$ fermi

  $\Rightarrow m_\pi \sim O(100 \text{ MeV})$

- "Immediate" confirmation
  1938-40: Cloud chamber found cosmic ray events with charged particles of $m \sim 100$ MeV.

- 1938-46: Many Problems with identifying this particle with Yukawa meson.

- Theory needed m_π <u>higher</u> than 100 MeV.

- " " τ_π <u>shorter</u> by factor 100.
  πN scattering stronger by

- " "

- π^+ (by Coulomb) prefer to decay rather than absorbed BUT
- π^- should be absorbed rather than decay.

→ Conversi – Pancini – Piccioni (Dec. 1946)

π^- in Carbon decayed rather than be absorbed

→ πN coupling 10^{-10} expected for Yukawa

Resolution of $\pi - \mu$ Puzzle (More particles!)

S. Sakata & T. Inoue (1943).

The 100 MeV C.R. meson is NOT the Yukawa meson but something else (μ). produced in the decay of π. They wrote down the complete coupling scheme (correctly) with the correct spins. & invented the second neutrino ν_μ. Their Proposal:

$\pi^+ \rightarrow \mu^+ \nu_\mu$ $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

ν_μ diff. from ν_e (maybe

$\bar{\nu}_e$ is the neutrino in $n \to p + e^- + \bar{\nu}_e$.

Similar proposals with <u>wrong</u> spin assignments were made by Y. Tanikawa (1942), Bethe & Marshak (1946).

The $\pi - \mu$ Scheme was completely confirmed with $m_\pi \sim 140$ MeV $m_\mu \sim 106$ MeV during/by 1947-8 by primarily the Bristol group's work with emulsion technique (Powell et al.)

Detection of ν_e and properties

Pauli had said it would be nice to see recoil momentum of final nucleus measured.

- This was done in '50's. (Crane & Halpern in U.S. ("finally"!) ↳ L.L.
- First Detection of $\bar{\nu}_e$.

Reines & Cowan 1954–56.

- First idea: use $\bar{\nu}_e$'s emitted during A-Bomb tests
- Better idea: use $\bar{\nu}_e$'s emitted in nuclear reactors. (Source)

$$U_{235} + n \longrightarrow X + Y + \text{few } n$$

X & Y neutron rich & decay by β

$$X \longrightarrow Z + e^- + \bar{\nu}_e \quad - - - .$$
$$\hookrightarrow Z' + e^- + \bar{\nu}_e$$

Detector: Use LS (proton-rich)

$$\bar{\nu}_e + p \longrightarrow n + e^+$$

$\hookrightarrow + e^- \longrightarrow 2\gamma$ (prompt

Nice tag signature

$\hookrightarrow n + p \longrightarrow d + \gamma\,(2.2\ \text{MeV})$

- Some early problems with claim of Reines – Cowan.

They claim to measure accurately the expected cross-section.

- But then in 1956 parity violation (suggested by Lee & Yang, confirmed by C.S. Wu et al.) followed by V-A theory (Sudarshan – Marshak, Feynman – Gell-mann)

→ This implied cross-section smaller by a factor of 2!!

After much discussion & re-analysis, Reines – Cowan agreed with the new prediction!!

Reason: neutron background higher than they thought.

Electron (K) – Capture

Consider β-decay with emission of e^+ & ν_e

$$A \longrightarrow B + e^+ + \nu_e$$

When $m_A c^2 < (m_B + m_e)c^2$ (but $m_A > m_B$)

This is forbidden by energy conservation.

But K (or electron) capture is possible:

$$A + e^- \text{ (from the atom)} \longrightarrow B + \nu_e$$

Neutrinos are Left-Handed

(Goldhaber, Grodzins & Sunyar 1957).

Beautiful Experiment (e⁻-capture)

$$Eu^{152} + e^- \longrightarrow Sm^{152\,*} + \nu_e$$

(spin 0) $\quad \tfrac{1}{2} \quad$ (spin 1) $\quad \tfrac{1}{2}$

$$\longrightarrow Sm^{152} + \nu_e + \gamma$$

$0 \quad \tfrac{1}{2} \quad 1$

Consider dir. of motion as z axis.

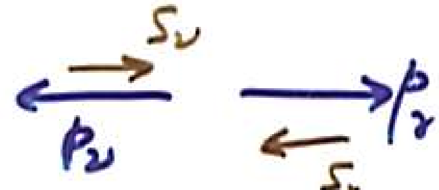
Then

Initial J_z		Final J_z
$\pm \tfrac{1}{2}$	=	$\pm \tfrac{1}{2} \quad \pm 1$

So $\quad +\tfrac{1}{2} = -\tfrac{1}{2} \quad +1$

or $\quad -\tfrac{1}{2} = +\tfrac{1}{2} \quad -1$

& to a good approx.



Spin (polarization) of photon measured by absorption in Fe in presence of $\underline{B}$ field.

$\Rightarrow$ S_ν & p_ν are opposite

$\Rightarrow$ ν_e is left handed.

Ensure that γ & ν are <u>NOT</u> in the <u>same</u> direction:

Otherwise correlation is lost.

For this choose only γ rays "forward"

By resonance absorption

1957 Two component neutrino

Landau, Lee-Yang, Salam.

- Weak Interaction maximally P.V.
- V−A.
- Then only ν_L & $\bar{\nu}_R$ participate
- In the $m_\nu = 0$ limit ν_R & $\bar{\nu}_L$ <u>never</u> show up.

· **1957-8** B. Pontecorvo suggests $\nu \leftarrow \bar{\nu}$ oscillations in analogy with $K^0 - \bar{K}^0$ oscillations.

But V-A makes ν LH, $\bar{\nu}$ RH; & osc. suppressed by $(m_\nu/E_\nu)^2$ - very small.

· **1962** {Z. Maki, M. Nakagawa & S. Sakata} in a remarkable paper: suggest that ν mass e-states & flavor e-states are NOT identical but:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad \begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

ν_1 & ν_2 have masses m_1 & m_2.

Propose similar mixing for "quarks" making up hadrons P, N, Λ and the fourth "charmed" particle. [Before Cabibbo (1963) & Bj/Glashow (1964) or GIM (1970)]

They also calculate oscillation length

$L \sim \delta m^2/4E$

& propose interpreting negative results of the on-going BNL expt. in terms of bounds on L & θ [exactly the way we do now]

1968-9. Pontecorvo works out many implications of ν-oscillations for solar & astrophysical neutrinos.

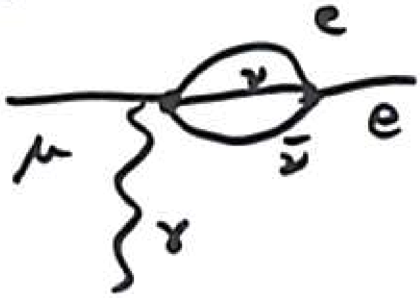
MNS (1962, 63) estimate $\begin{cases} \mu \to e\gamma \\ \nu_2 \to \nu_1 \gamma \end{cases}$

- G_F (eff) depends on Q-value
- Kinks in β-ray spectra at various m_{ν_i}.

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(\frac{\delta m^2 L}{4E}\right)$$

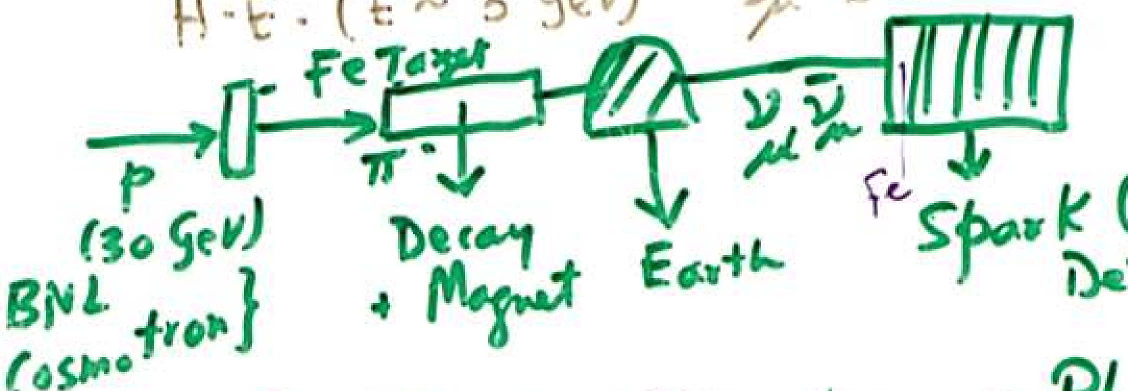
Columbia - BNL Two Neutrino Experiment (1961-2)

- By 1960, it was clear that if $\nu_\mu \equiv \nu_e$, $\mu \to e\gamma$ would have been seen [indep. of a full theory of weak int.] [esp. due to G. Feinberg]



- Settle the issue exptlly.

[M. Schwarz suggested using BNL to get H-E. (E ~ 5 GeV) ν_μ Beams (1960)]



$\pi^- \to \mu^- + \bar{\nu}_\mu$

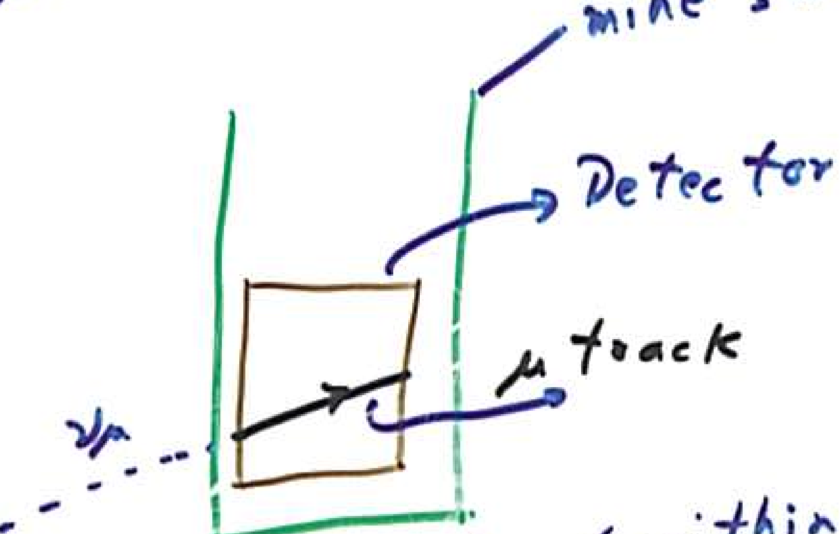
$\pi^+ \to \mu^+ + \nu_\mu$

In Spark Chamber + Plates

$\bar{\nu}_\mu + p \to n + \mu^+$
↳ Track

$\bar{\nu}_\mu + p \to n + e^+$ No events of this kind seen.

1965. M.G.K. Menon et al. in Kolar Gold field, S. India (Tata-Osaka-Durham)
F. Reines et al. in CWI Goldmine S. Africa (Case-Wits...)
observe ν_μ's made in the atmosphere (first "natural" neutrinos) deep underground. [3000 m].
Horizontal tracks of μ's made in the rocks.



. Rate roughly (within factor 2) consistent with expectation.
. First bounds on Astrophysical ν's.

KGF– The 1st reported Atmospheric ν

Several detectors in KGF mine at various depths.

3 ν published 15 Aug 65

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

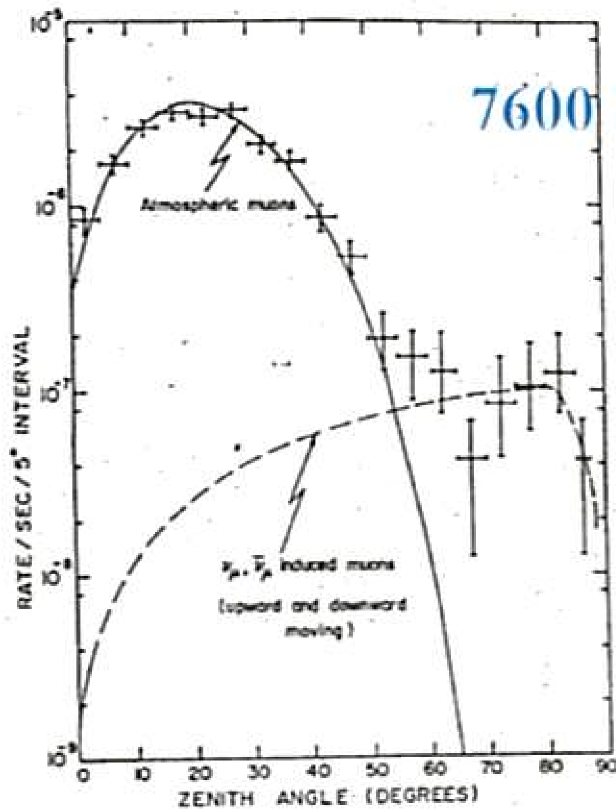
C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

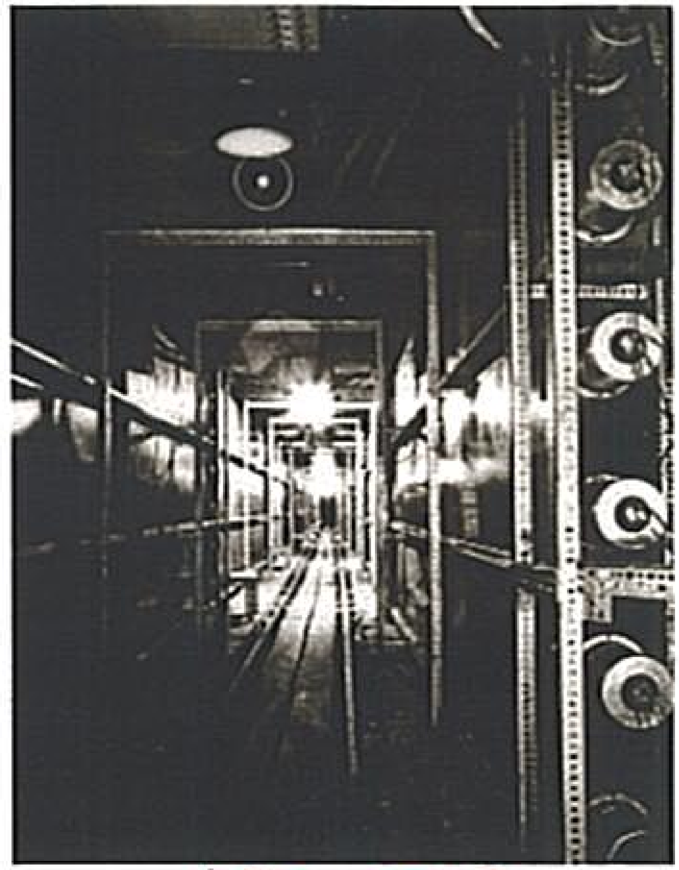
Event number	Type of coincidence	Projected zenith angle	Date	Time
1	TEL.2 N_4+S_4	37°	30.3	20.04
2	TEL.1 N_1+S_1	48 ± 1°	27.4	18.26
3	TEL.2 N_6+S_6	75 ± 10°	25.5	20.03

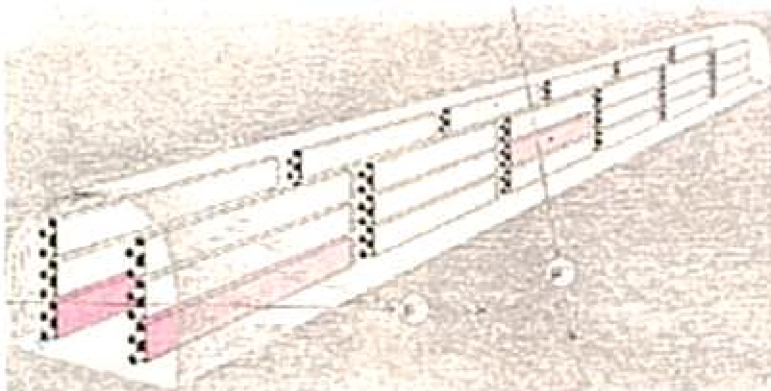


Rate lower by a factor of 2 from expected

CWI – The 1st recorded Atmospheric ν

First ν
February 29, 1965
Recorded 100 (1/month)





KGF- CWI
Early indication of Atmospheric Neutrino Anomaly?

Maury Goodman, Neutrino 2002
"Other Atmospheric ν Experiments"

Third Lepton & Neutrino

Perl et al. SLAC (1976)

$$e^+ + e^- \longrightarrow \mu^\pm + e^\mp + X$$

anomolous events seen. Finally showed to be due to:

$$e^+ + e^- \longrightarrow \tau^+ + \tau^-$$

τ has decay modes

$$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau$$
$$\to \mu^- + \bar{\nu}_\mu + \nu_\tau$$
$$\to \pi^- + \nu_\tau$$
$$\to 2\pi + \nu_\tau$$
$$\vdots$$

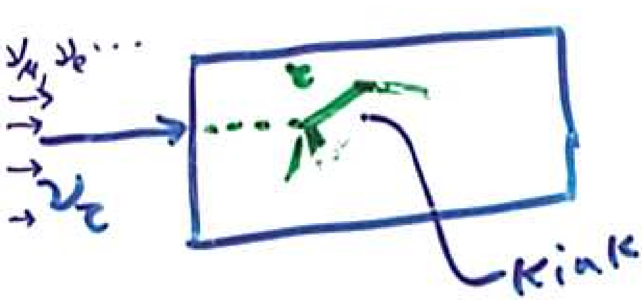
. $m_\tau \sim 1.7$ GeV.

Detection of ν_τ

DONUT @ FNAL (2000).

Track in Emulsion:

$pp \to D_s + X$; $D_s^+ \to \tau^+ \nu_\tau$ with B.R. of 3%



$\nu_\tau + N \to \tau^- + X$ in Emulsion

$\tau \to$ decays $\to \pi\pi\pi + \nu$, $\to e + \nu\nu$ etc.

$$L_\tau \sim \gamma c \tau_\tau \sim \frac{E_\tau}{m_\tau} c\tau_\tau \sim 1 \text{ mm} \quad (E \sim 10 \text{ GeV})$$

1987 Feb. 23

SN 1987A observed optically. (naked eye).

Neutrino (presumably $\bar{\nu}_e$) signal seen in Kamiokande & IMB

18 events, $E_\nu \sim 7$ to 30 MeV.

Consistent with expectations for a $T \sim 4$-6 MeV.

Many constraints could be placed on ν properties with these few events.

- neutronization $e^- p \to n \nu_e$ ($\sim$ ms)
- $e^+ e^- \to \nu_\alpha \bar{\nu}_\alpha$ (few sec)

(Type II) $E \gtrsim 30$ MeV. $T \sim 5$ MeV

How Many Kinds of Neutrinos?

ν_e, ν_μ, ν_τ - - - - ..

1989. SLC @ SLAC
LEP @ CERN

establish only 3 kinds of (light) neutrinos which participate in weak interactions.

$e^+e^- \longrightarrow Z^0$ (90 GeV/c^2)

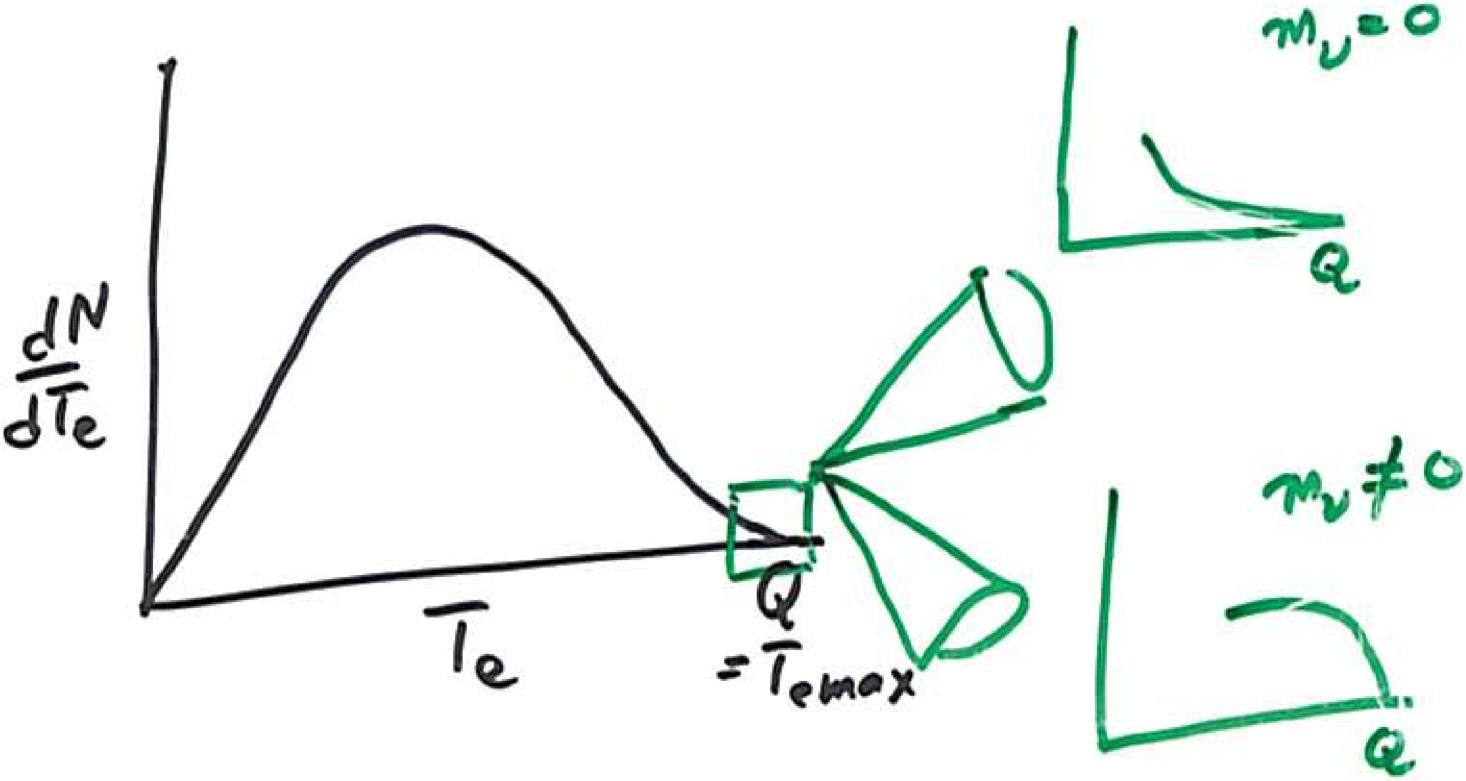
$Z^0 \longrightarrow \sum_i \nu_i \bar{\nu}_i$ (Invisible width)

$$B.R. \frac{(Z^0 \rightarrow all\ \nu's)}{(Z^0 \rightarrow all)} \propto N_\nu$$

$N_\nu = 3$ with high accuracy.

Neutrino Mass, Mixing & Oscillations

- Direct Mass Measurements
  - Tritium Beta Decay.
  - Fermi's result.



Current Bound (Mainz, Troitsk)

$$\langle m_\nu \rangle < 2.2 \text{ eV}$$

$$\langle m_\nu \rangle = \sqrt{\sum_i |U_{ei}|^2 m_{\nu_i}^2}$$

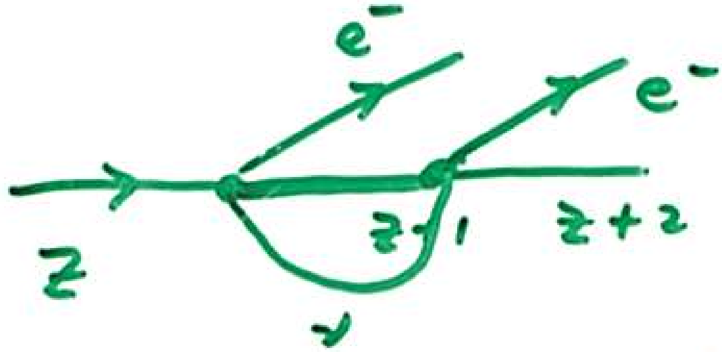
· Double Beta Decay (ν-less).

· Majorana (1934) Neutrino

$\nu \equiv \bar{\nu}$ (Current theory Prejudice)

[Dirac Neutrino $\nu \neq \bar{\nu}$].

· Then ν-less $\beta\beta$ Possible



$(N, Z) \longrightarrow (N, Z+1) + e^- + \nu$

$\longrightarrow (N, Z+2) + e^- + e^-$

$Q = E_{e_1} + E_{e_2}$ = line

· Rate $= \frac{1}{\tau} \propto \langle m_{\beta\beta} \rangle$

· Current Bound (Heidelberg)

$\langle m_{\beta\beta} \rangle \approx O(1\ eV)$.

$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right|$ can be cancellations

$= (M_\nu)_{ee}$

Cosmology & Neutrinos

- Existence of Neutrino "microwave" Background
  - "T_ν" ~ 2°K
  - n_ν ~ 300/cc (all flavors $\nu + \bar{\nu}$)

Detection ⟹ ?

- Constraint on $\Sigma_\nu = \sum_i m_{\nu_i}$

Large Scale Structure spectrum
power suppressed at smaller scales.

- Lyman Alpha Forest data
- 2dF GRSurvey
- CMB · (WMAP)

⟹ $\Sigma_\nu < 0.63$ to 1 eV.

- $\Omega_\nu = \left(\frac{\rho_\nu}{\rho_{crit}}\right)$ – can be ~ 0.01
  – comparable to $\Omega_{\text{Luminous matter}}$

- If $n_\nu = n_{\bar\nu}$, then $\nu + \bar\nu$ count as one (Dirac) fermion.

$$n_\nu + n_{\bar\nu} = \frac{3}{4}\left(\left(\frac{4}{11}\right)^{1/3}\right)^3 n_\gamma = \frac{3}{11} n_\gamma$$

$$\simeq 110/cc \text{ per flavor } \begin{Bmatrix} 55 \text{ for } \nu_\alpha \\ 55 \text{ for } \bar\nu_\alpha \end{Bmatrix}$$

- If N families have mass m_ν (in eV)

then $u_\nu = N m_\nu (110)$ eV/cc.

- $$\Omega_\nu = \frac{u_\nu}{\rho_c} = \frac{N m_\nu (110) \text{ eV/cc}}{h^2 (10572) \text{ eV/cc}}$$

$$\simeq \frac{N m_\nu}{(95\text{eV}) h^2} \simeq \frac{N m_\nu}{(47\text{eV})}$$

- e.g. if $N = 3$, $m_\nu \sim$ eV $\Rightarrow \Omega_\nu \sim 0.06$
- e.g. if $N = 1$, $m_\nu = 0.07$eV $\Rightarrow \Omega_\nu \sim 0.0015$ (Super-K) Comparable to luminous matter

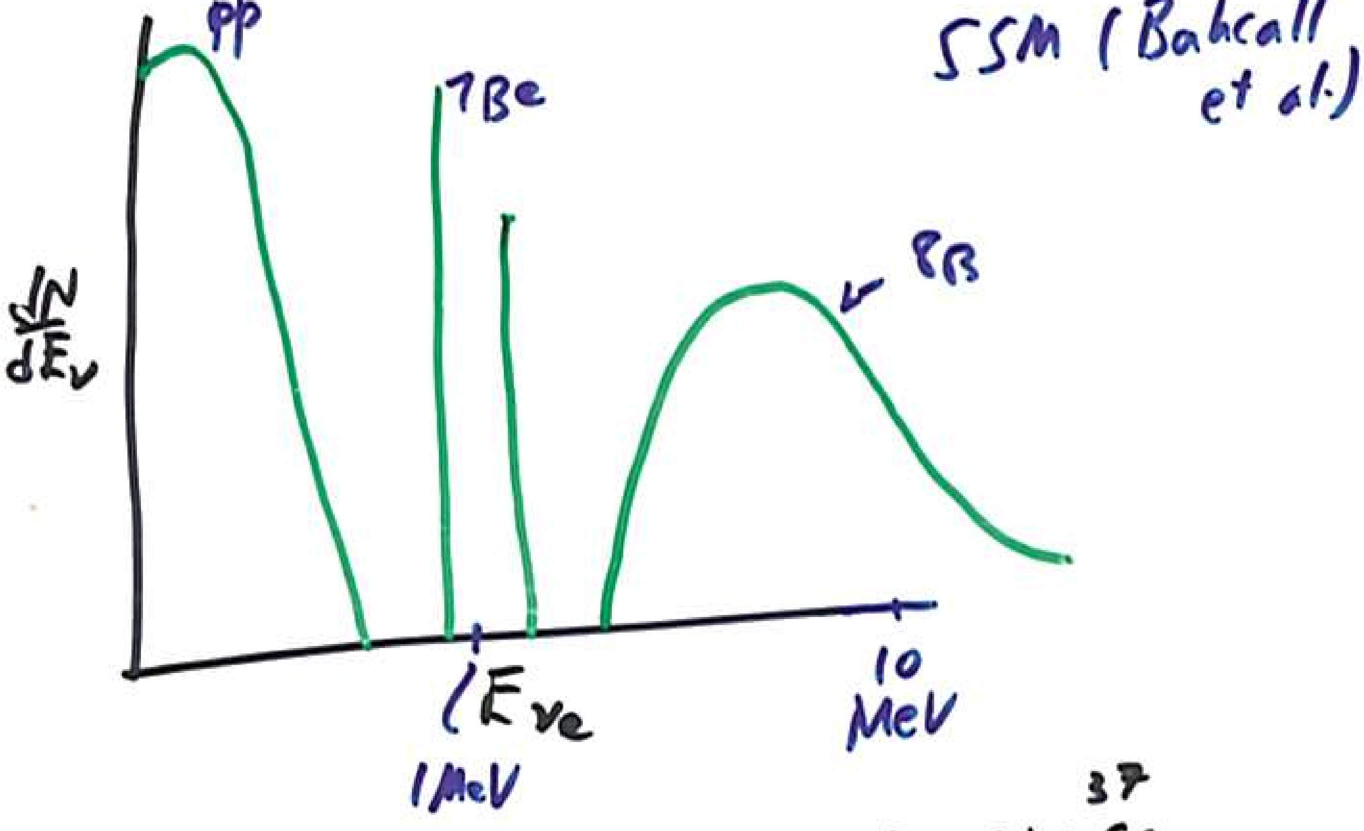
Neutrino Oscillations

Yield info on δm_{ij}^2 & U_{ij}.

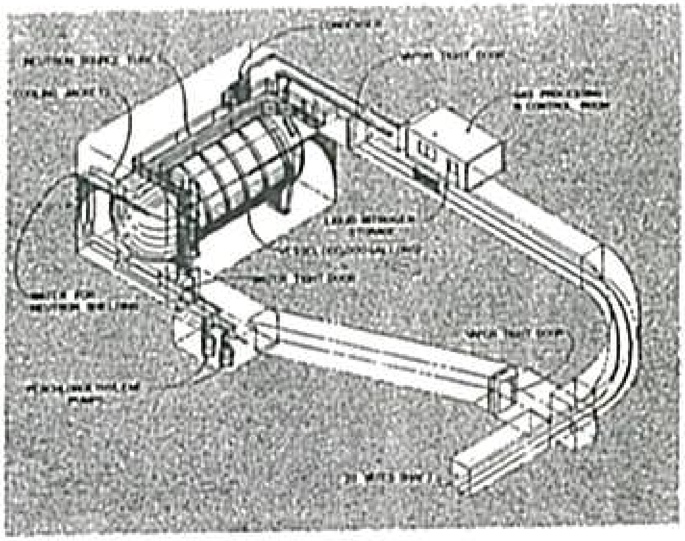
• Solar Neutrinos

Energy of sun : $4p \to {}^4He + e^+ + e^+ + \nu_e + \nu_e$

Expected Neutrino Spectrum:

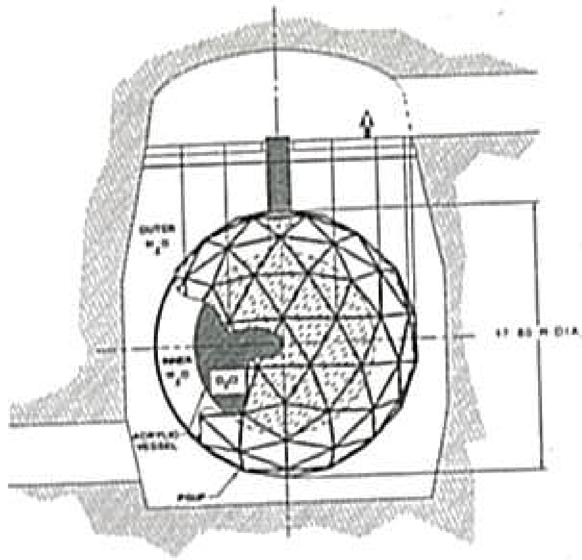


- Ray Davis (1964 –) $\nu_e + {}^{37}Cl \to {}^{37}Ar + e^-$
  detect ^{37}Ar chemically
- Kamiokande (1988–94) $\nu_e + e^- \to \nu_e + e^-$
  detect e^- - forward
- Gallex & SAGE (1990 –) $\nu_e + {}^{71}Ga \to {}^{71}Ge + e^-$
  detect ^{71}Ge chemically



Homestake

$\nu_e + Cl \rightarrow Ar + e$



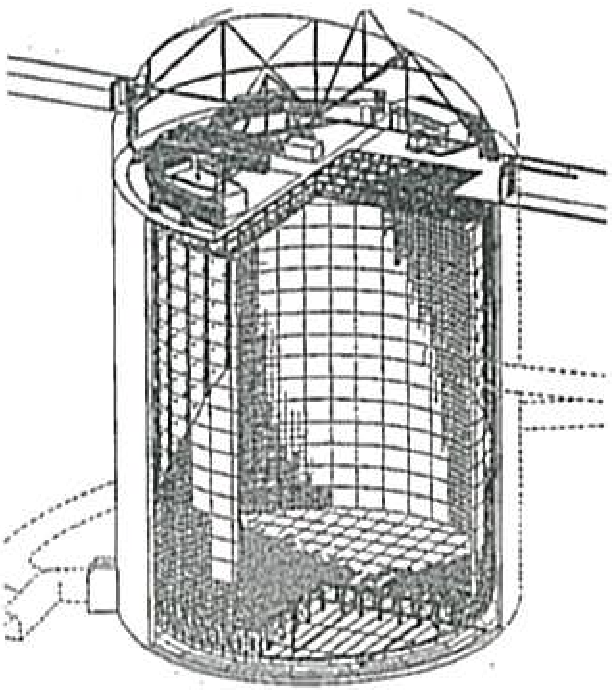
SNO

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

Flux Monitor $\left\{ \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \right\} + D \rightarrow \nu' + p + n$

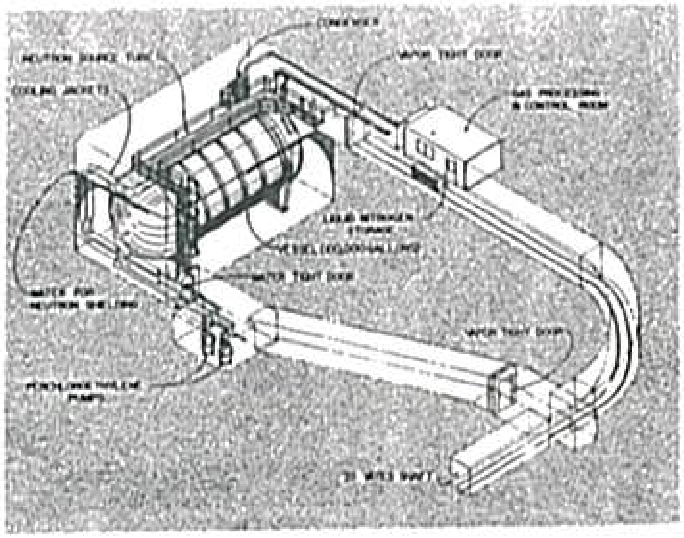
$\nu_e e \rightarrow \nu_e e$

Removes the need to depend on Solar model.



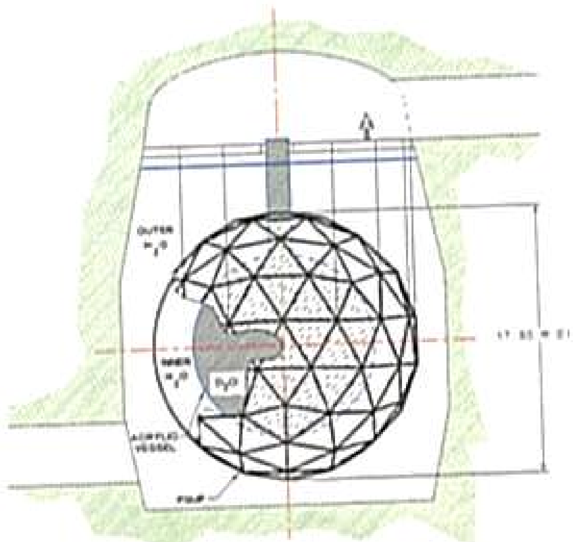
Super-Kamiokande

$\nu_e + e \rightarrow \nu_e + e$



Homestake

$\nu_e + Cl \rightarrow Ar + e$

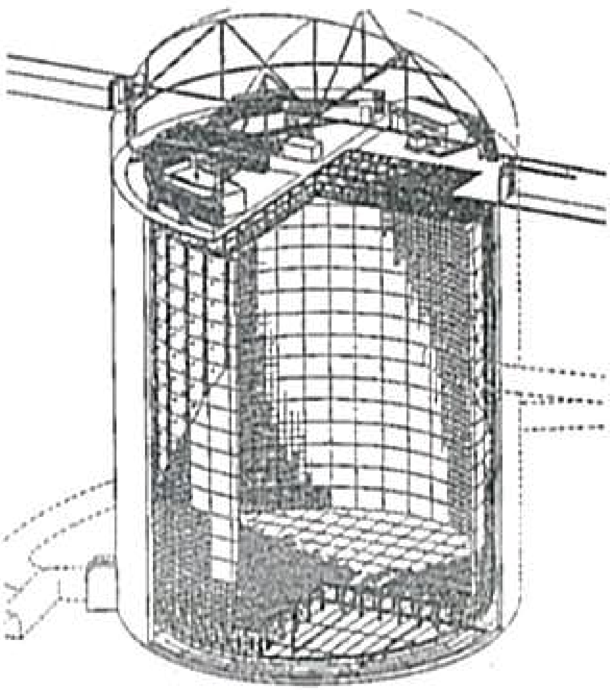


SNO

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

Flux Monitor $\left\{ \begin{array}{l} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right\} + D \rightarrow \nu' + p + n$

$\nu_e e \rightarrow \nu_e e$



Super-Kamiokande

$\nu_e + e \rightarrow \nu_e + e$

$\bar{\nu}_e$'s from Reactors

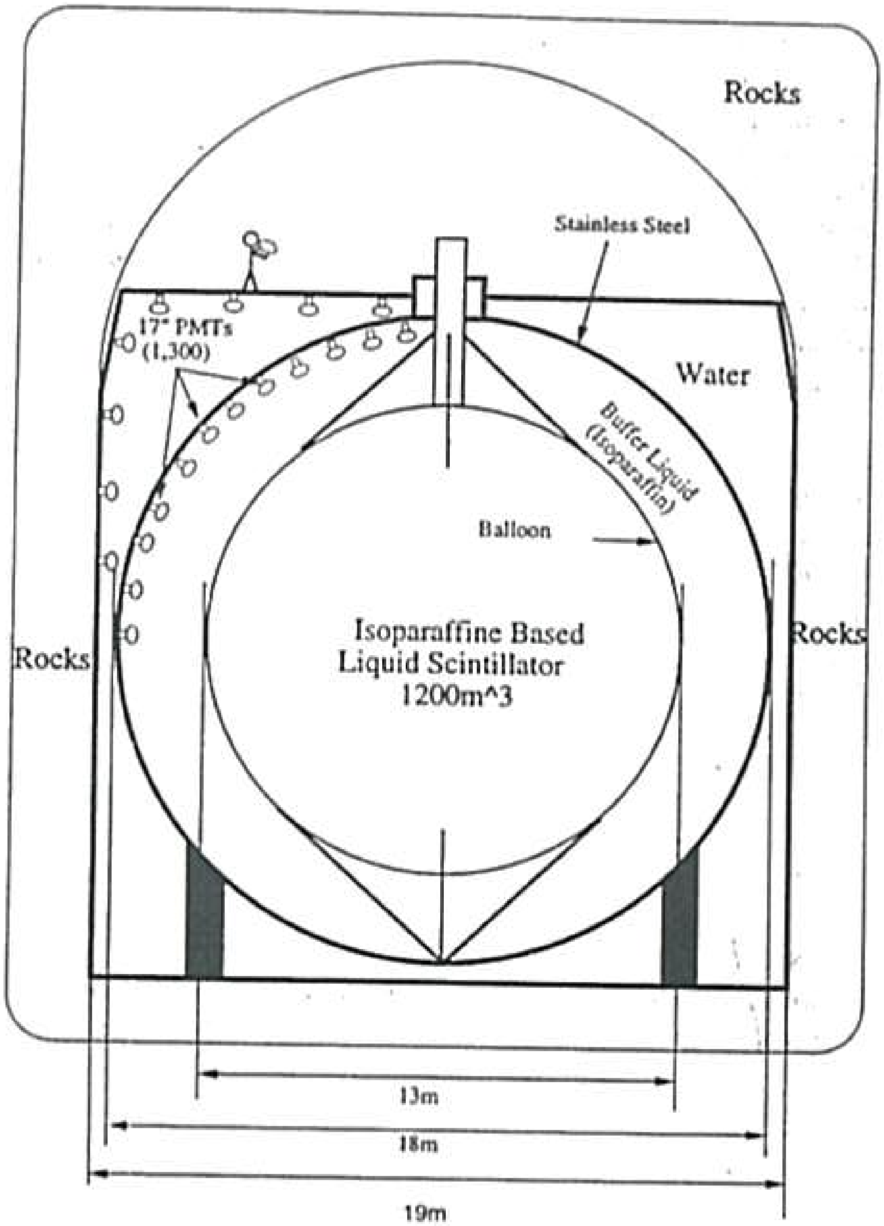
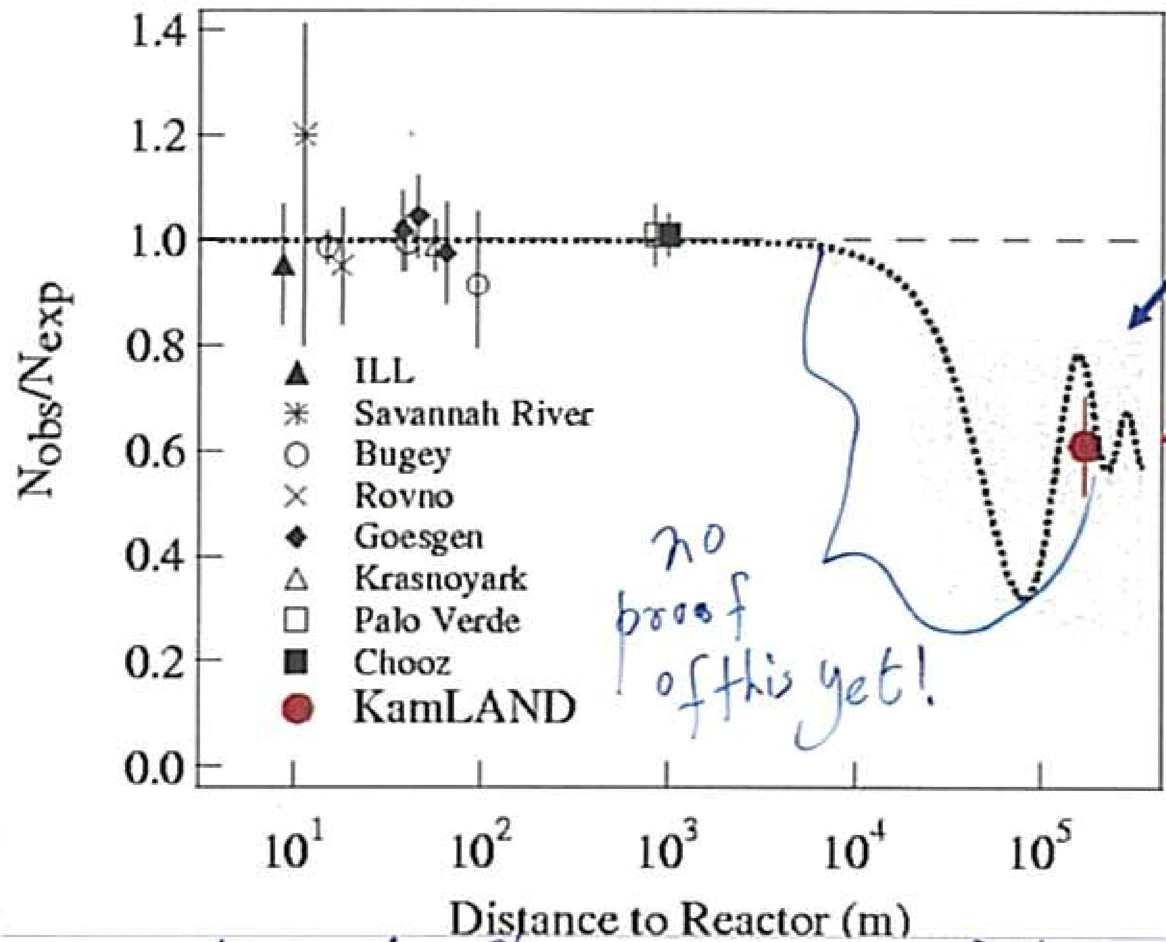


Figure 1: Schematic view of the KamLAND detector.

Ratio of Measured to Expected $\bar{\nu}_e$ Flux from Reactor Neutrino Experiments



Shaded region LMA solution at 95% C.L.

Dotted curve
$\sin^2 2\theta = 0.833$
$\Delta m^2 = 5.5\times10^{-6} eV^2$

KamLand Plus Solar ν_e Data fix the parameters

• SNO (2001–) $\begin{cases} \nu_e + {}^2D \to e^- + p + p \\ \nu_e + {}^2D \to \nu + p + n \end{cases}$

Detect e^- →

Detect n →

Current Status:

• ν_e oscillates into other ν's (mixture of ν_μ & ν_τ)

• $\delta m^2 \sim (5-10)10^{-5}\ eV^2$

• $\theta \sim 30°$

• Atmospheric Neutrinos:

$$p_{C.R.} + (Nucl.)_{air} \longrightarrow \pi^{\pm} + X.$$

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu_\mu / \bar{\nu}_\mu$$

$$\hookrightarrow e^{\pm} + \nu_e + \nu_\mu$$

• For energies $E_\nu < 10$ GeV

$$\# \nu_\mu / \# \nu_e \sim 2/1$$

(at higher E μ's don't decay in 20 km of atm. but lose E). (so v. few ν_e's)

In 1986-8 Detectors (water č) made to find p-decay found

$\#\nu_\mu / \#\nu_e \sim 1/1$ instead.

Strongest evidence from Kamiokande (Koshiba et al.) but not compelling.

Finally in 1998, Super-Kamiokande found v. strong evidence for

ν_μ oscillations.

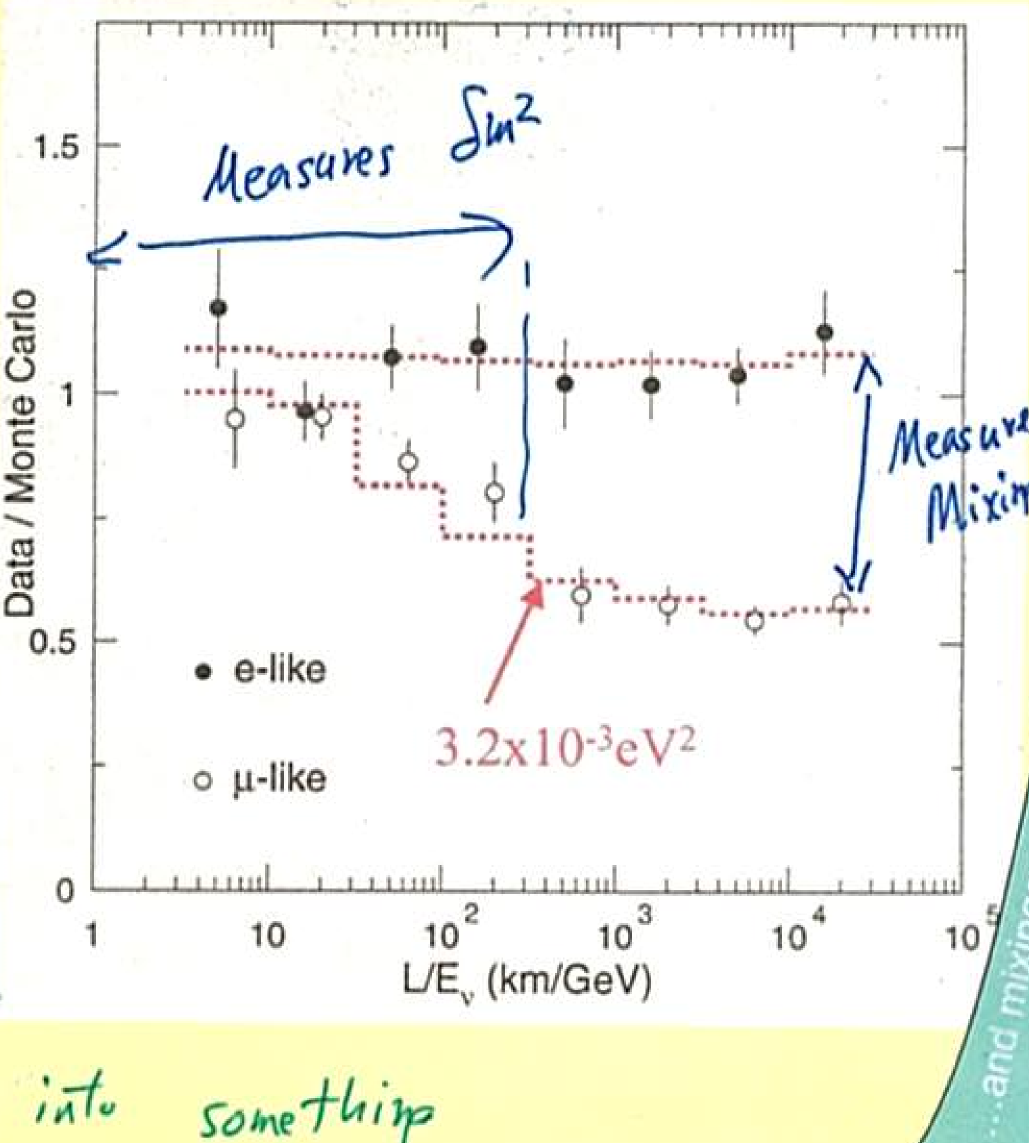
Current status:

- ν_μ oscillates mostly to ν_τ.
- $\delta m^2 \sim (~~3-6~~ 2) 10^{-3}\ eV^2$
- $\theta \sim 45°$.

History of Atmospheric ν "Anomaly"

17

n of L/E_ν



in$^2(1.27\Delta m^2 L/E_\nu)$

ence

"oscillates" into something

man made ν_μ's from K2K.

...and mixings

Dave War

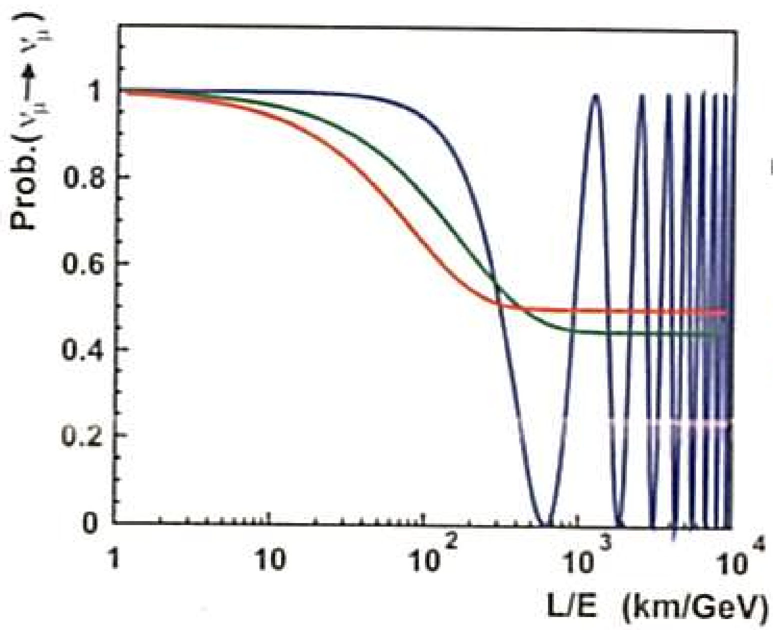
University of Sussex/

L/E analysis

Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$

Neutrino decay : $P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \times \exp(-\frac{m}{2\tau}\frac{L}{E}))^2$

Neutrino decoherence : $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times (1 - \exp(-\gamma_0 \frac{L}{E}))$



6 T F F W F O U T X J U I I

⇨ The first dip can be observed

→ Direct evidence for oscillations

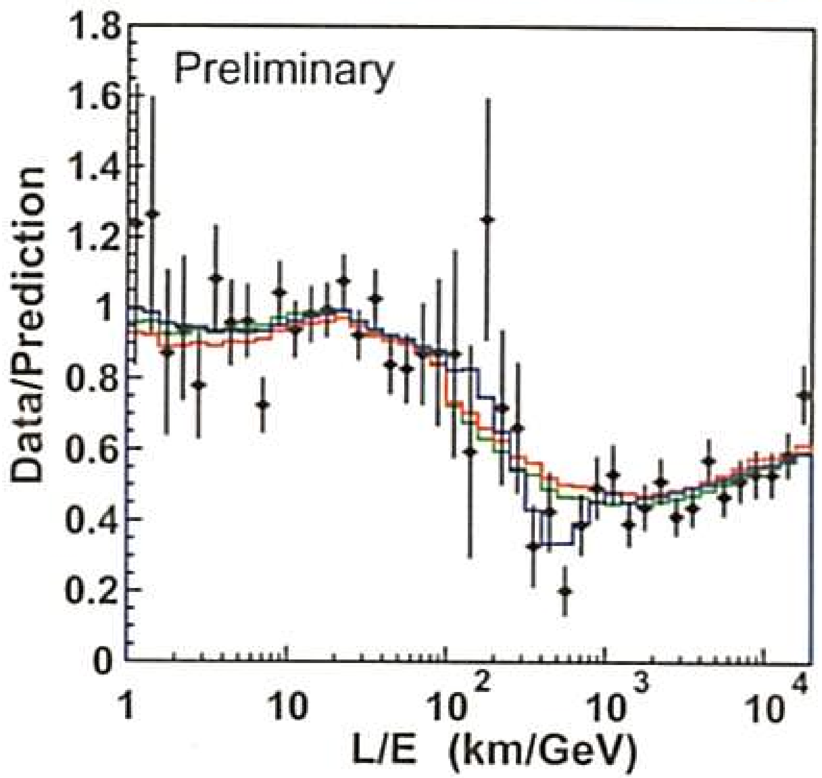
→ Strong constraint to oscillation parameters, especially Δm^2 value

5FTUT GPS OFVUSJO

— **Oscillation** χ^2_{min}=37.8/40 d.o.f

— **Decay** χ^2_{min}=49.2/40 d.o.f → $\Delta\chi^2$=11.4

— **Decoherence** χ^2_{min}=52.4/40 d.o.f → $\Delta\chi^2$=14.6



3.4 σ to ν decay

3.8 σ to ν decoherence

First dip observed in data cannot be explained by alternative hypotheses

Ishitsuka @ NooN 2004 TOKYO Feb. 2004

Conclusions

Measurement of L/E dependence of flavor transition probability

First dip was observed as expected from neutrino oscillation

→ **cannot be explained by alternative hypotheses (3.4 σ to ν decay, 3.8 σ to ν decoherence)**

→ **gives strong constraint to neutrino oscillation parameters**

$1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} eV^2$

$0.90 < \sin^2 2\theta$ at 90%C.L.

consistent with zenith angle analysis

First evidence that neutrino transition probability obeys sinusoidal function as predicted in neutrino oscillation

Current Knowledge

- mixing matrix U

$$U \sim \begin{pmatrix} c_\theta & -s_\theta & \varepsilon \\ s_\theta/\sqrt{2} & c_\theta/\sqrt{2} & -1/\sqrt{2} \\ s_\theta/\sqrt{2} & c_\theta/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

(c_θ: measured in Solar ν's; ε: Constrained by CHOOZ; $1/\sqrt{2}$: measured in Atm. ν's)

- $\theta \sim 30^\circ$
- $\varepsilon < 0.2$ (from Reactor Expts. at SBL CHOOZ, BUGEY)

$\delta m^2_{12} \sim (7 \cdot 10) \cdot 10^{-5}\ eV^2$

$\delta m^2_{23} \sim (2 - 5) \cdot 10^{-3}\ eV^2$

- magnetic dipole moments

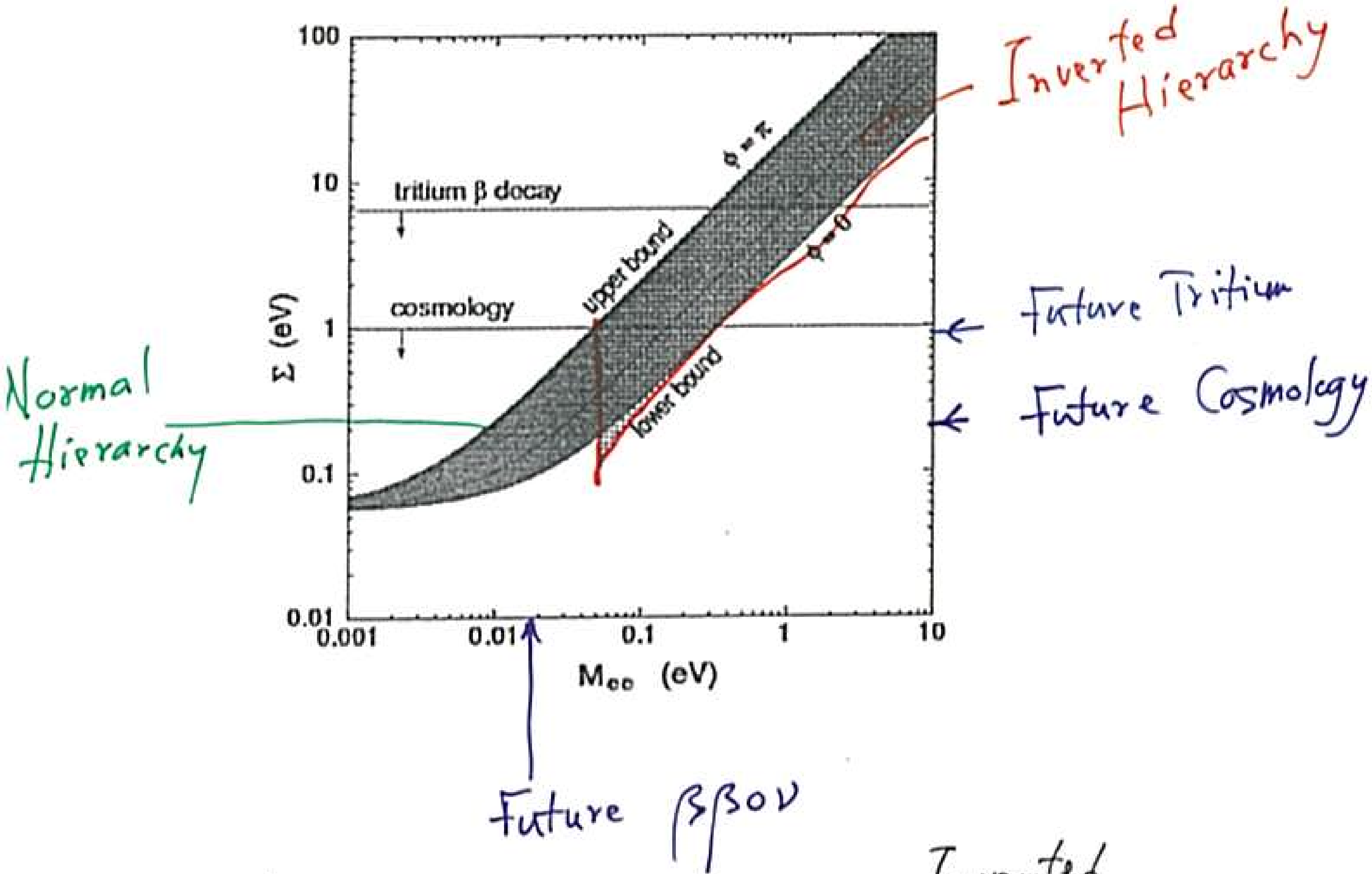
  typical bound $\mu_{\nu_e} < 10^{-10}\,\mu_{Bohr}$

- Lifetimes

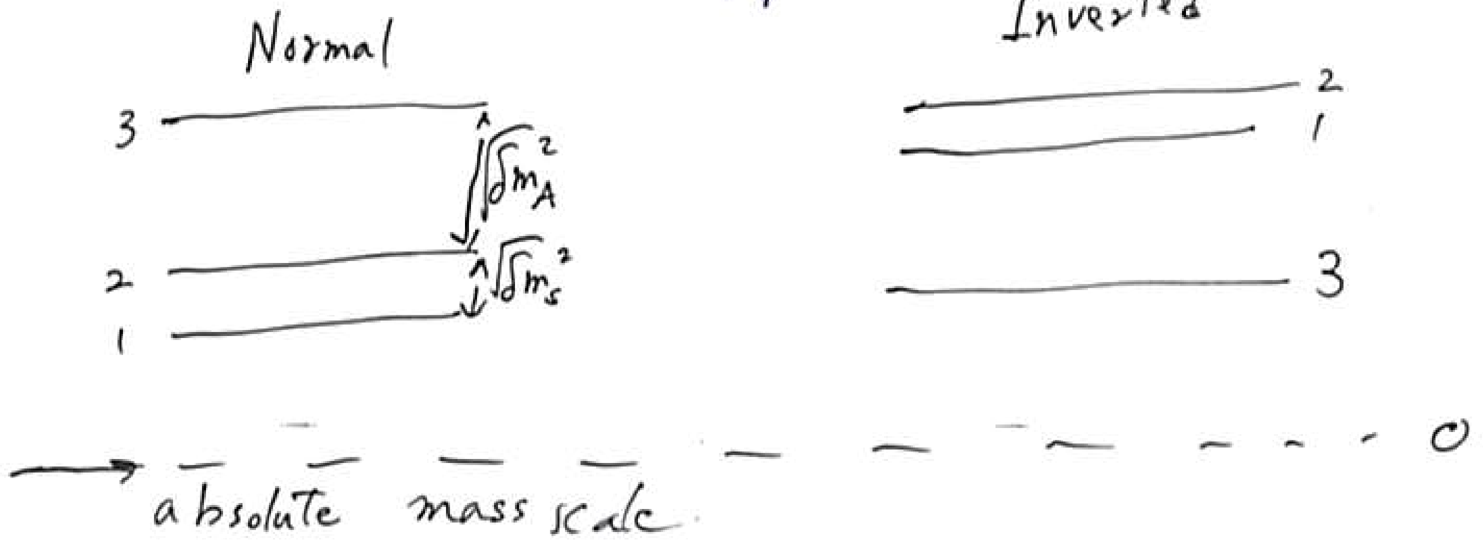
  from Solar data →

  $\tau_\nu \gtrsim 10^{-4}\ s$ ($m \sim 1\,eV$).

  ↳ $10^{-2}\ s$



100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
Σ (eV)
M_ee (eV)
tritium β decay
cosmology
upper bound
lower bound
φ = π
φ = 0
Inverted Hierarchy
Normal Hierarchy
Future Tritium
Future Cosmology
Future ββ0ν



Normal
Inverted
3
2
1
2
1
3
$\sqrt{\delta m_A^2}$
$\sqrt{\delta m_s^2}$
0
absolute mass scale

Future

- Neutrino Properties
  - Better (much) of the mixing matrix
    - remaining entries e.g. U_{e3}
      many proposals e.g. Reactor expts
    - phase δ in mixing matrix ($\nu \longleftrightarrow \bar{\nu}$)
      ν "factories" (μ-storage rings).
    - mass hierarchy matter effects
    - absolute Masses
      - Tritium End Point (Katrin)
      - ν-less Double Beta Decay (Many Proposals)
    - Cosmology

· See red dips of osc.

LBL expts: MINOS, JHF, CERN - - - -

- Magnetic / Electric Dipole Moment
  MUNU $\longrightarrow 10^{-12} \mu_{Bohr}$
- Lifetime Current Bound : $\tau > 10^{-2}$ s (Kamland)
  Can be improved to 10^{+4} s with H.E. ν's

- Some Uses of Neutrino Telescopes

- Neutrino Telescopes of KM3 size and larger will be <u>built</u>!

  - ICECUBE at South Pole
  - ANTARES/NESTOR in meditarranean

- Astrophysical Neutrino Sources with detectable fluxes with high energies (upto & beyond PEV $= 10^6$ GeV) and at distances $\sim 10^3$ MPC exist!
  (e.g. AGN's & GRB's (at lower energies)

- Then ⟶

Astrophysical Neutrino Sources

High energy neutrino fluxes expected to be produced in "cosmic accelerators" which accelerate protons.

Eg, Gamma Ray Bursts (GRBs) and Active Galactic Nuclei (AGNs)

pp and pγ collisions produce charged pions → Decay to neutrinos

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\downarrow$$
$$\bar{\nu}_\mu + e^+ + \nu_e$$

Expected flavor ratio at the source: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

Caveat: If μ's absorbed or lose energy no ν_e's → 0 : 1 : 0

Sub-dominant prompt ν's → 1 : 2 : ϵ

The ratio of flavours at the source is expected to be

$$\nu_e : \nu_\mu : \nu_\tau = 1:2:0$$

In the limit of exact $\nu_\mu - \nu_\tau$ symmetry, the ratios in the mass basis are:

$$\nu_1 : \nu_2 : \nu_3 = 1:1:1$$

(Learned & S.P. 1995)

Exact mu-tau symmetry occurs when: $\theta_{atm} = 45°$ and $\theta_{13} = 0$

independent of the solar angle

Since: oscillation length is <<< distance to source

→ Averaged oscillations (incoherent mixture of mass eigenstates)

→ 1:1:1 in the flavor basis (or any basis)

If we see 1:1:1 → Boring.

Confirms our prejudice.

If we don't see 1:1:1

Different flavor ratio at the source
Eg. 0:1:0 (Rachen and Meszaros, 1998) (magnetic fields)
→ becomes 0.5 : 1 : 1 at Earth

Exotic neutrino properties
- Neutrino decay upto 10^5 s/eV ⇒ measure mixing parameters!
- CPT violation
- Oscillation to steriles with very tiny delta δm^2 → upto 10^{-18} eV^2
- Pseudo-Dirac mixing
- 3+1 or 2+2 mixing
- Magnetic moment transitions (Dirac ν's)

Current Bounds on ν_i Lifetimes

- Invisible 2 body Modes

- ν_1 : SN1987A
$$\Longrightarrow \quad \tau_1 \geq 10^5 \text{ sec/eV}$$

- ν_2 : Solar $\bar{\nu}_e$ limit (KamLand)
$$\Longrightarrow \quad \tau_2 \geq \begin{cases} 5 \cdot 10^{-2} \text{ s/eV} & (QD) \\ 10^{-5} \text{ s/eV} & (H) \end{cases}$$

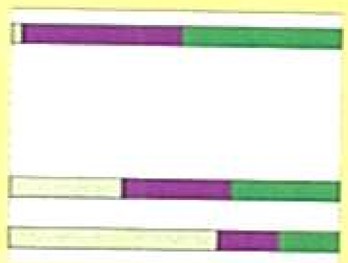
- ν_3 : Atm. Neutrinos (Super-K Dip)
$$\tau_3 \geq 10^{-10} \text{ s/eV}$$
(Normal Hierarchy only)

[To explain LSND need $\tau \sim 10^{-12}$ s/eV]

Decay – Flavor Ratios

The lightest neutrino should be stable.

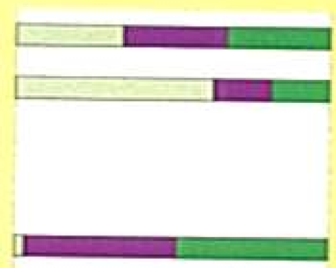
Normal hierarchy



$\nu_e : \nu_\mu : \nu_\tau = 5:1:1$

$= U_{e1}^2 : U_{\mu 1}^2 : U_{\tau 1}^2$

Inverted hierarchy



$\nu_e : \nu_\mu : \nu_\tau = 0:1:1$

$= |U_{e3}|^2 : |U_{\mu 3}|^2 : |U_{\tau 3}|^2$

Such extreme deviations of the expect ratios, 1:1:1, should be identifiable in current or planned neutrino telescopes, such as IceCube

If MNSP matrix is <u>not</u>

$$U = \begin{pmatrix} c & s & 0 \\ s/\sqrt{2} & c/\sqrt{2} & 1/\sqrt{2} \\ s/\sqrt{2} & c/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}, \text{ CPV phase } \delta = 0$$

BUT

$$U = \begin{pmatrix} & & U_{e3} \\ & & \\ & & \end{pmatrix} \quad \begin{matrix} U_{e3} \neq 0 \\ \delta \neq 0 \end{matrix}$$

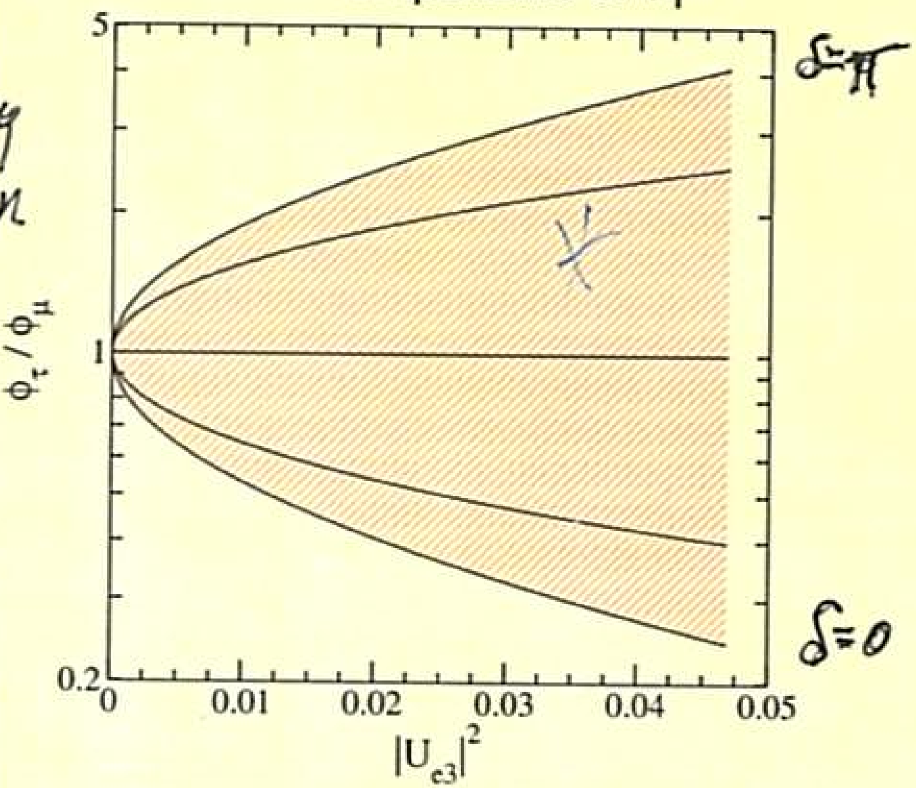
Then →

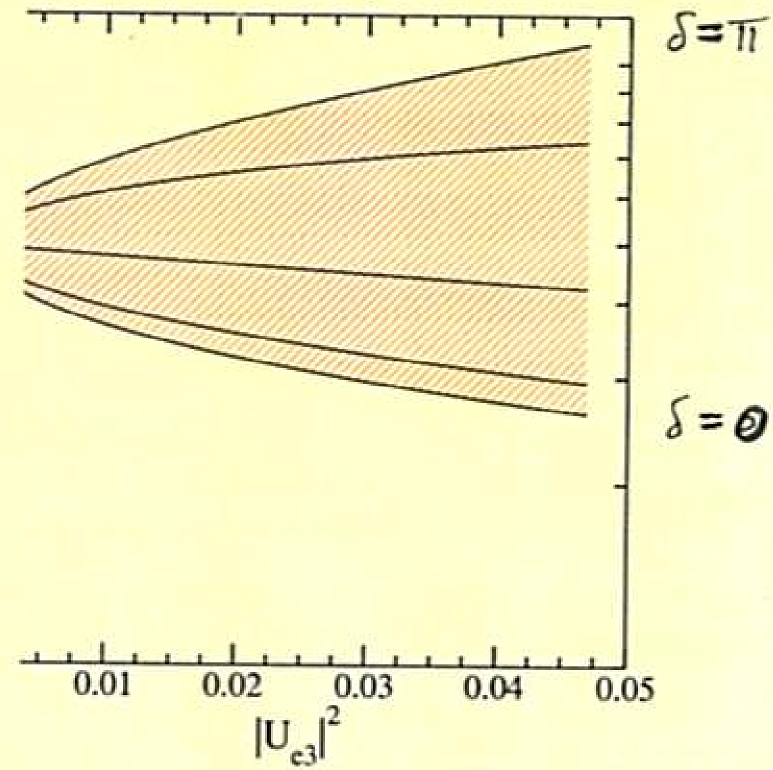
Measuring U_{e3} & δ ($\cos\delta$)

Neutrino decay, and sensitivity to θ_{13} and the CP phase δ

Nonzero θ_{13} breaks mu-tau symmetry

τ/μ Symmetry broken

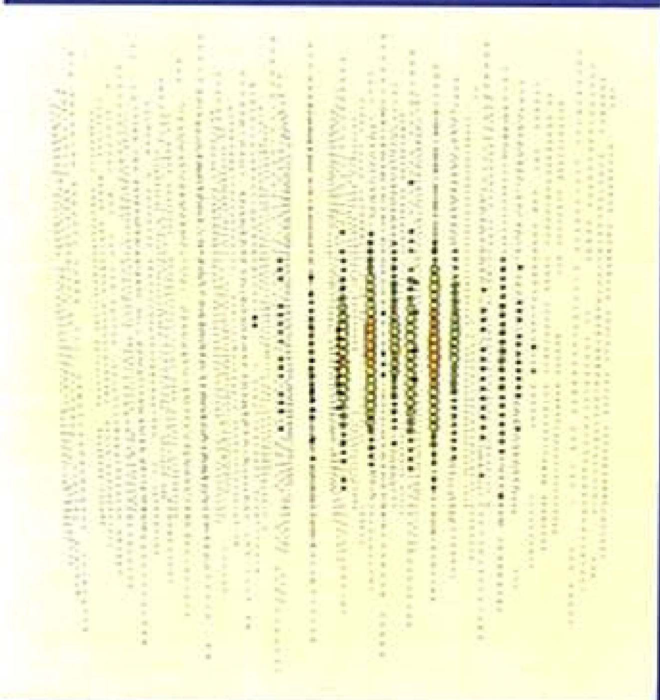


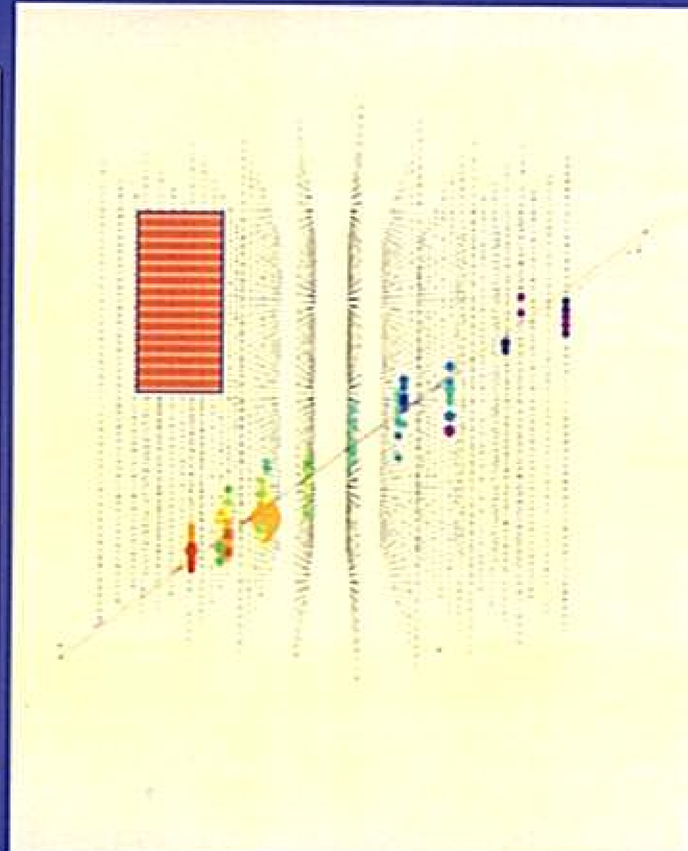


Beacom, Bell, Hooper, Pakvasa & Weiler 13

Normal Hierarchy Measurement of U_{e3} & δ byproduct!!

Flavor Identification

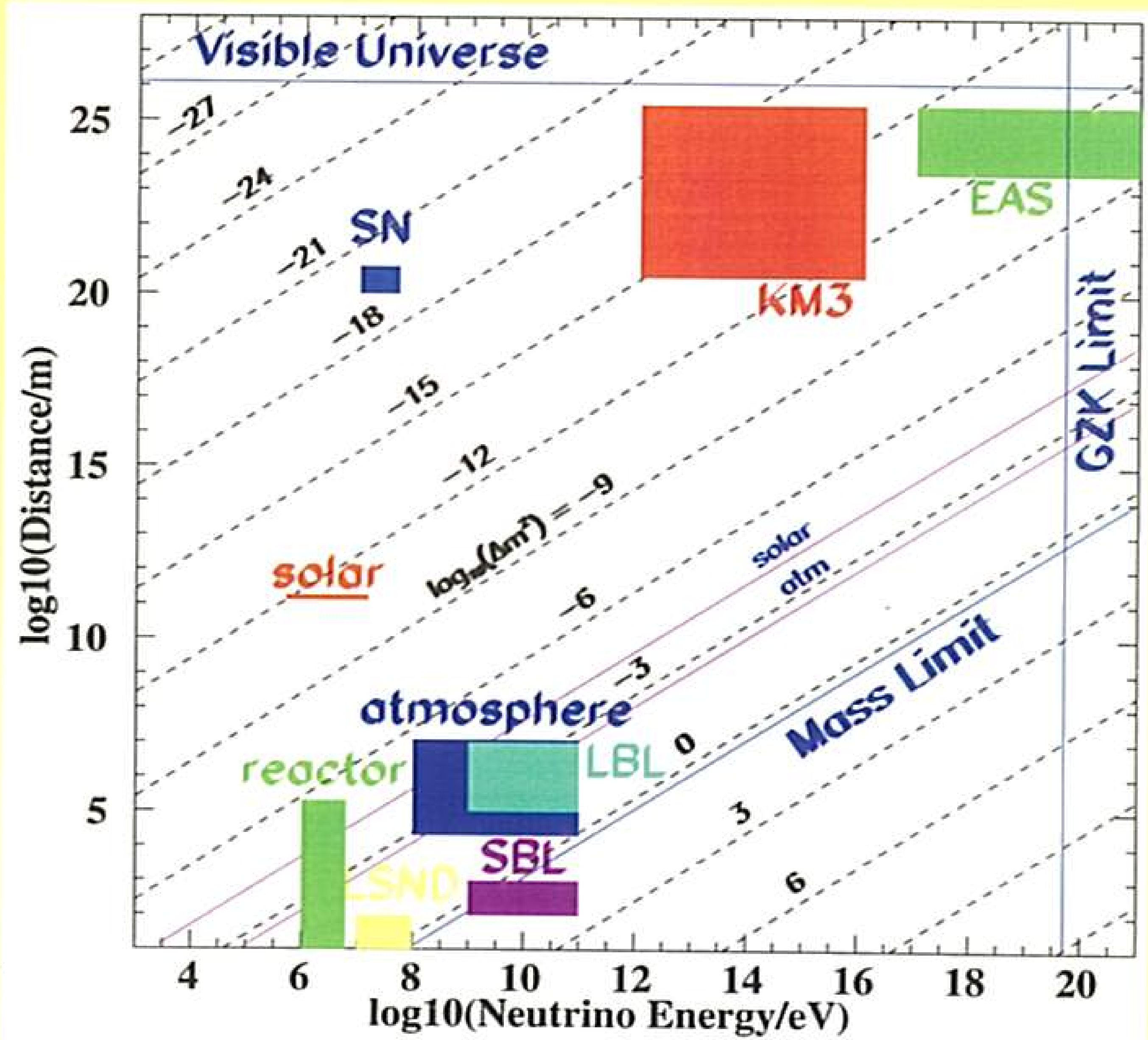




~ 100 TeV ν_e $\quad$ ~ 10 TeV ν_μ $\quad$ ~ 10 PeV ν_τ

The Ultimate Long Baseline Experiment!

The "Learned Plot"



→ Lines correspond to $\frac{\delta m^2 L}{4E} \simeq O(\frac{\pi}{2}) \sim O(1)$

Pseudo-Dirac Neutrinos

Suppose:

Neutrinoless double beta decay experiments reach a sensitivity where we expect a positive signal (say, because we had confirmed the inverted hierarchy) but we get a null result.

Does that mean neutrino masses are of Dirac type?

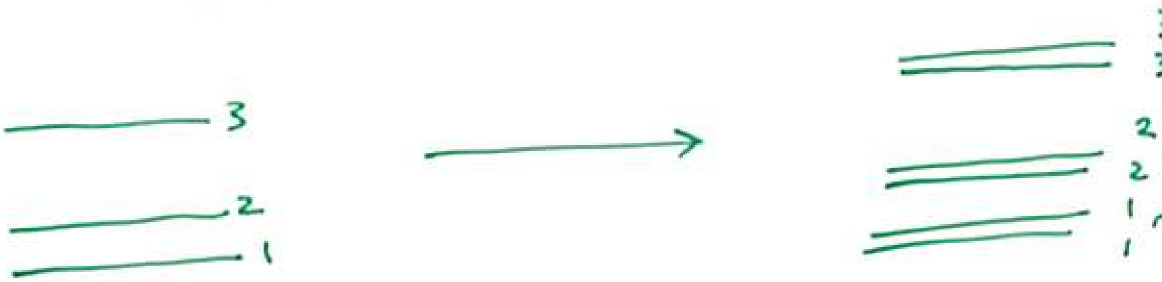
Not necessarily: they might be pseudo-Dirac. (Wolfenstein)

Majorana mass terms might be subdominate in size to Dirac terms.

The fundamental question would still remain:
Do Majorana mass terms (of any size) exist in nature?

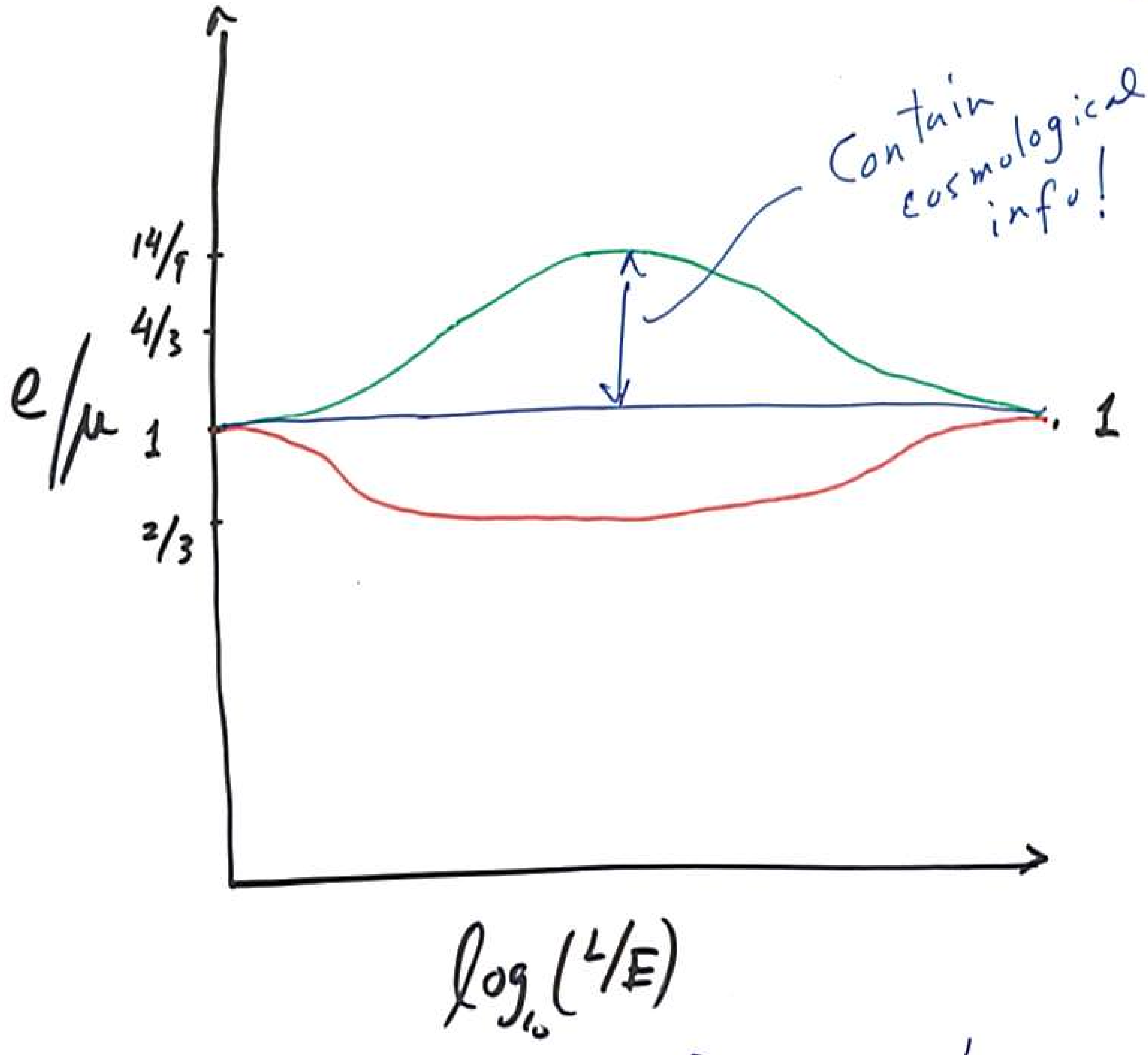
Can Such small mass Differences be probed? How?

- Pseudo-Dirac Neutrinos with $10^{-18}\,eV^2 < \delta m^2 < 10^{-12}\,eV^2$



- no new mixing angles or phases
- $P_{\alpha\beta} \longrightarrow \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \left[1 - \sin^2 \frac{\delta m_j^2 L}{4E}\right]$
- $m_{eff}^{\beta\beta} \longrightarrow \sum_i U_{ei}^2\, \delta m_i^2 / 4 m_i^2 \rightarrow < 10^{-6}\,eV.$
- Effect on flavor Ratios.

If $\delta m^2 < 10^{-12}\,eV^2$, no experiments with terrestrial (or solar) neutrinos can ever detect it.



Probing Pseudo-Dirac ν's with $10^{-16} eV^2 \lesssim \delta m^2 \lesssim 10^{-12} eV^2$

If $\delta m^2 < 10^{-12} eV^2 \Rightarrow$ Can Do

Cosmology with Neutrinos

- When distances are cosmological.

L in $\delta m^2 L / 4E$ is replaced by

f where:

$$f = z/H \left[1 - \frac{(3+q_0)}{2} z - - - - \right]$$

So
$$P_{\alpha\beta} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 (1 - \sin^2 \phi_j)$$

$$\phi_j = \left(\frac{\delta m_j^2}{4E} \right) f$$

f contains Cosmological Information

(Weiler, Simmons, Learned, S.P.)
1994

If enough data available to fix δm_j^2, then can determine: z, H & q_0

- Since only used microscopic information no dependence on evolution, standard candles ....
- First confirmation of Hubble red shift using particles other than photons.
- ν Red Shifts = γ Red Shifts?
- No need for distance measurements

ν's & SETI

- Advanced Civilisation may need to use physics limit timing info.
- shortest known lifetime is τ_Z
- Possible use of ν's from Z-decays as timing signals.

→ Look for 45 GeV ($= m_Z/2$) ν's in ν-Telescopes - - - .

Neutrino Geophysics

- Heat outflow at earth surface $\sim 40\,TW$
- Expected contribution (90% from U & Th) from radiogenic $\sim 16\,TW$

  (with ^{238}U & ^{232}Th abundances ~ Solar system)
- Detailed Distribution of U & Th in mantle & crust <u>not known</u>

  but modelled.

  e.g. 50% in mantle
  50% in crust
  (not much in oceanic crust).
- Heat from U/Th activity (α-β) correlated with $\bar{\nu}_e$ flux
- $\bar{\nu}_e$ from U & Th have different energies.

8.C.2

Nuclear Physics **78** (1966) 657—662; © *North-Holland Publishing Co., Amsterdam*

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TERRESTRIAL NEUTRINOS

GERNOT EDER

Institut für Theoretische Physik der Universität Giessen, Giessen, Germany

Received 11 October 1965

bstract: Arguments are given for a remarkable abundance of radioactive elements within the earth. Methods are discussed in order to measure this abundance by neutrino experiments.

1. Introduction

The chemical composition of the interior of the earth is still quite unsure. There-re it would be an advancement if one could measure the abundance of selected emical elements by their neutrino emission. In this connection, potassium, thorium d uranium are of interest. Generally it is assumed that these elements are confined ainly to the earth's crust, if only for that reason that the material obtainable from e earth's mantle shows a small portion of the mentioned substances. On the other nd the exchange of material between the earth's crust and the upper mantle can ve rise to a reduction of radioactive elements in this region. Further there are ar-

GEOPHYSICS BY NEUTRINOS*)

G. Marx

Institute of Theoretical Physics, Roland Eötvös University, Budapest

A review of the possibilities for the chemical exploration of the central regions of the Earth is given, making use of the antineutrino flux produced by natural radioactive isotopes.

1. INTRODUCTION

It was suggested many years ago that the neutrino and antineutrino luminosity of different celestial bodies might provide means of exploring the internal structure of these objects (see e.g. [1]). Due to the enormous mean free path the neutrinos and antineutrinos provide valuable direct information, which is not available with other methods. Searching the Sun with a neutrino telescope is well under way [2]. The present paper is concentrated on the second important task of neutrino physics: the Earth. The idea of observing terrestrial antineutrinos is not a new one [1, 3, 4, 5]. Here a review of different experimental possibilities will be given.

• Assuming no Geo-reactor

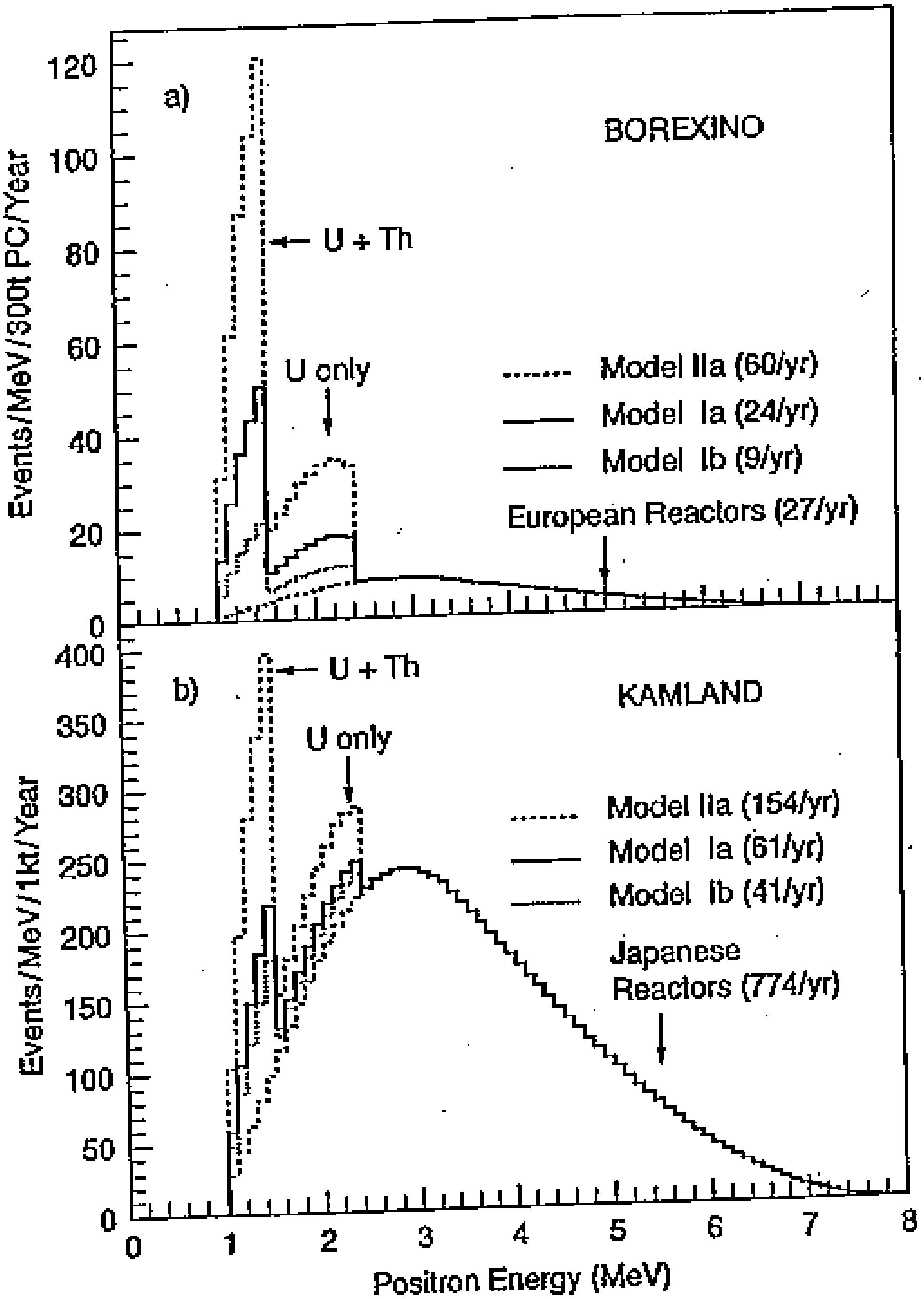
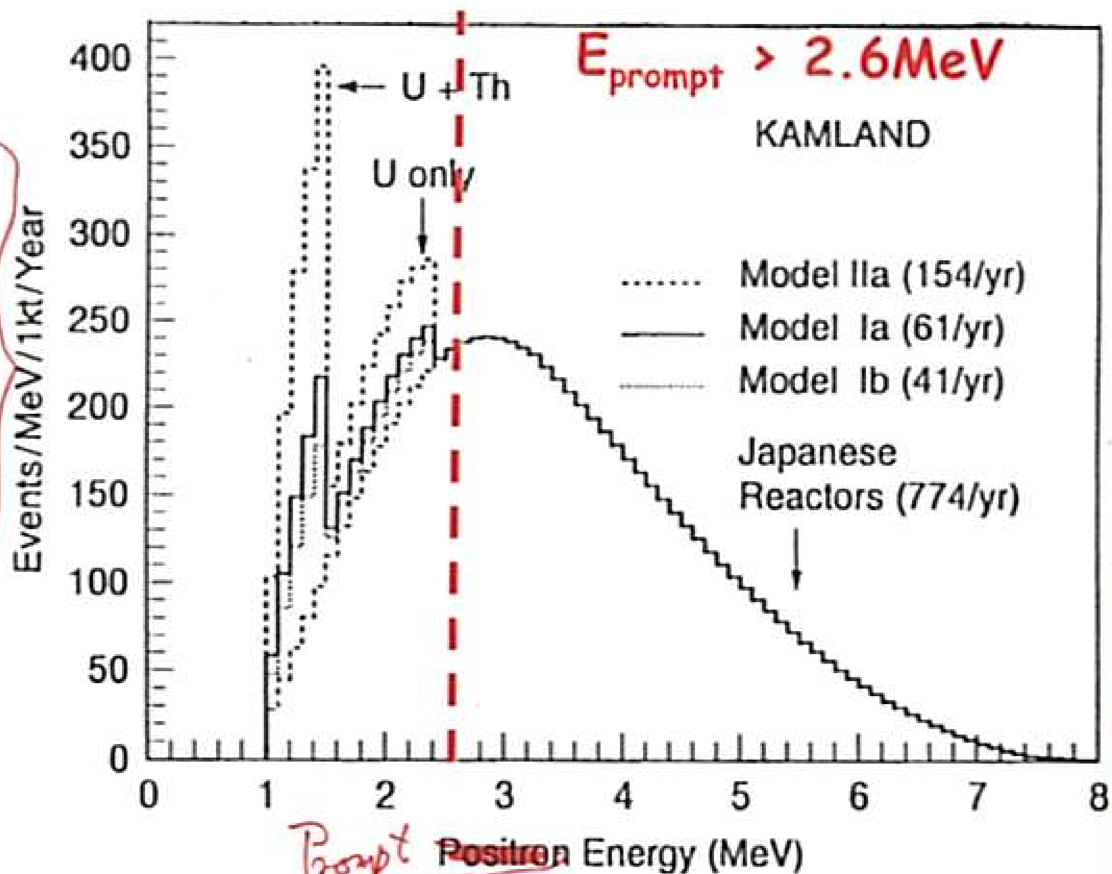


FIG. 2. $\bar{\nu}_e$ (positron) signal spectra from the Earth and from nuclear reactors at Borexino (a) and at Kamland (b). The signal rates point to several years of measurement for data of statistical significance to different aspects of geophysical interpretation.

Calculated Geoneutrino Energy Spectrum

Raghavan, Schoenert, Enomoto, Suekane, Shirai, A. Suzuki, PRL 80 (1998)



$E_{e^+} \cong E_{\bar{\nu}} - \Delta$ (1.8 MeV)

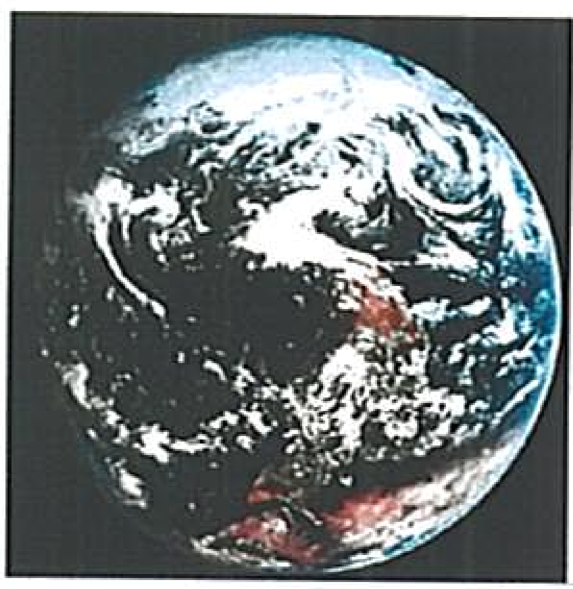
$E_{prompt} = E_{e^+} + m_e$

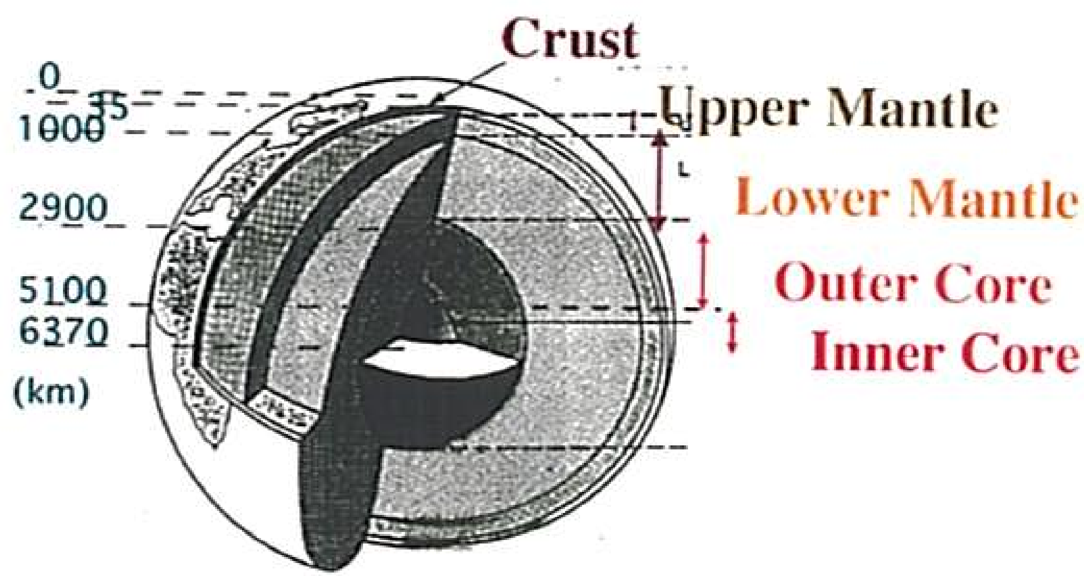
$\approx E_{\bar{\nu}} - 0.8$ MeV

First Direct Measurement of Geoneutrinos and Earth's Radiogenic Heat

◎ Radiogenic Heat (40 - 60% of 40 TW) from U / Th (Crust, Mantle) Decays

◎ Basic Factor in Interior Dynamics and History of the Present Earth





Oscillation Spectrum

93% C.L. consistent with neutrino oscilations spectrum

But...

53% C.L. consistent with renormalized no oscillation spectrum
Clearly needs better statistics.

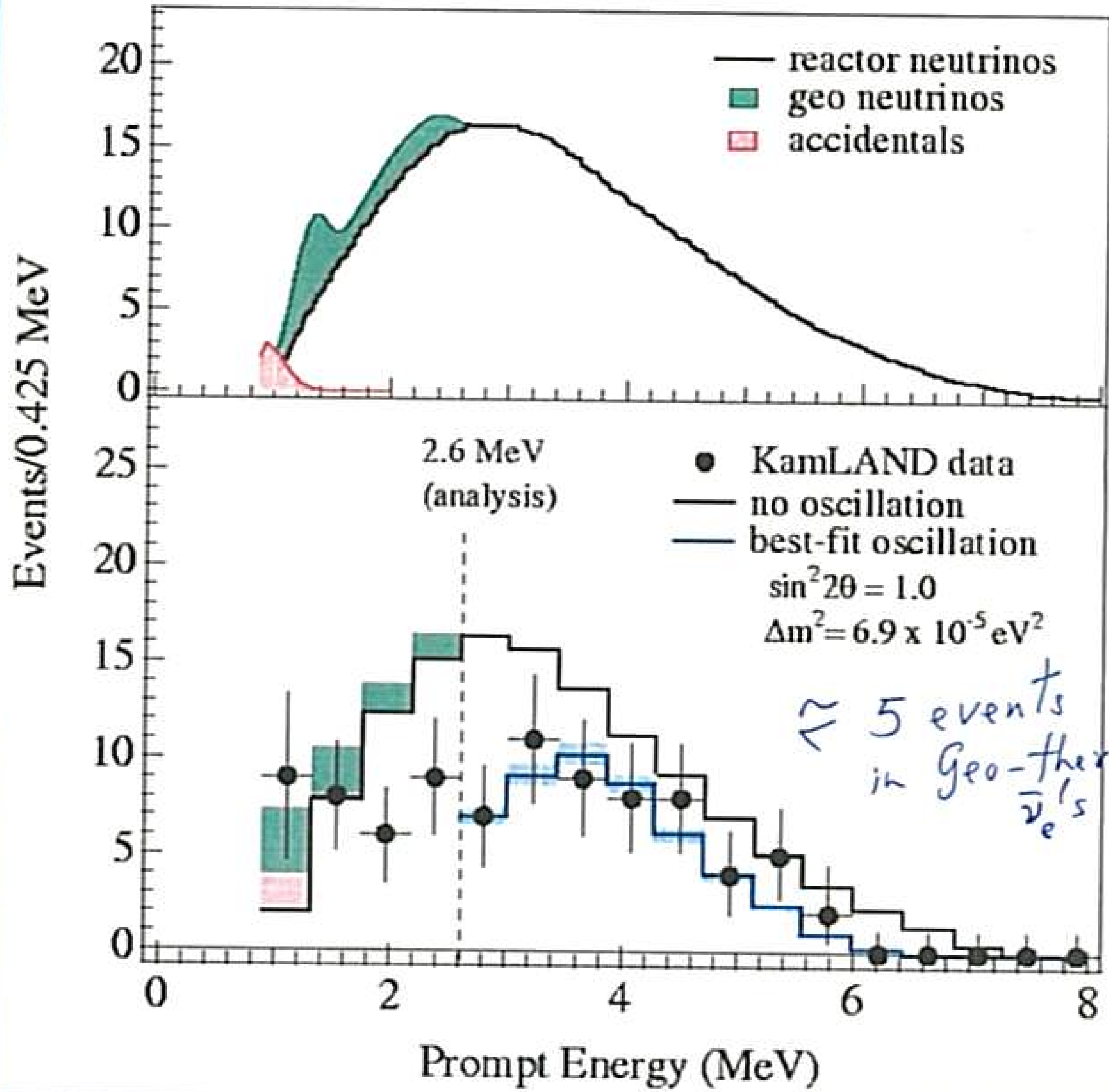
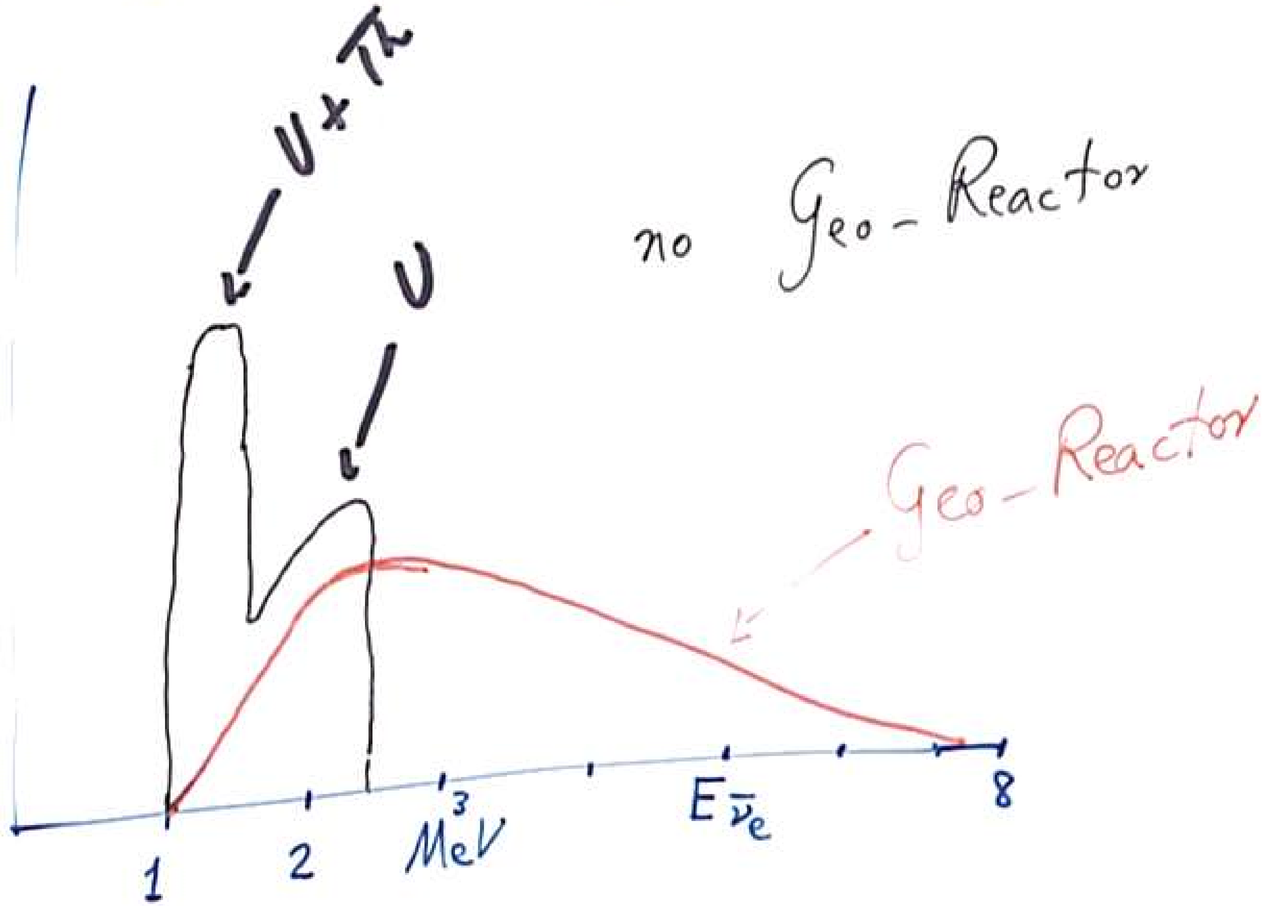


Table 2. Calculated $\bar{\nu}_e$ fluxes [$\times 10^6$ cm^{-2} s^{-1}] for sites around the world.

Site	Location	Uranium crust	Uranium mantle	Thorium crust	Thorium mantle	Total (U + Th)	Reactor backgro
Gran Sasso Lab (Italy)	42°N 14°E	1.8	1.4	1.5	1.2	5.9	0.65
Kamioka Mine (Japan)	36°N 137°E	1.5	1.4	1.3	1.2	5.4	1.5
Sudbury (Canada)	47°N 81°W	2.3	1.4	1.9	1.2	6.8	1.3
Central Australia	25°S 133°E	1.9	1.4	1.6	1.2	6.1	0.016
Himalayas (Tibet)	33°N 85°E	2.5	1.4	2.1	1.2	7.2	0.054
Pacific Ocean (Hawaii)	20°N 156°W	0.22	1.4	0.16	1.2	3.0	0.027
Geographic Maximum		2.3	1.4	1.9	1.2	6.8	
Geographic Minimum		0.15	1.4	0.11	1.2	2.9	

For a detector in pacific ocean (using Kamland bounds) Counting Rate due to U/Th $\bar{\nu}_e$'s is ~ 50,000/day



The "Georeactor" Model

- An unorthodox model
  - Chief proponent: **J.M.Herndon**
- The model
  - A fuel breeder fission reactor in the Earth's sub-core
  - **Size:** ~4 miles radius
  - **Power:** 3-10 TW

The Georeactor Model

What we can all agree on:

1. The Earth is made of the **same stuff as meteorites**
2. In its earliest stages, the Earth was **molten**
3. The Earth gradually **cooled**, leaving all but the outer core in solid form

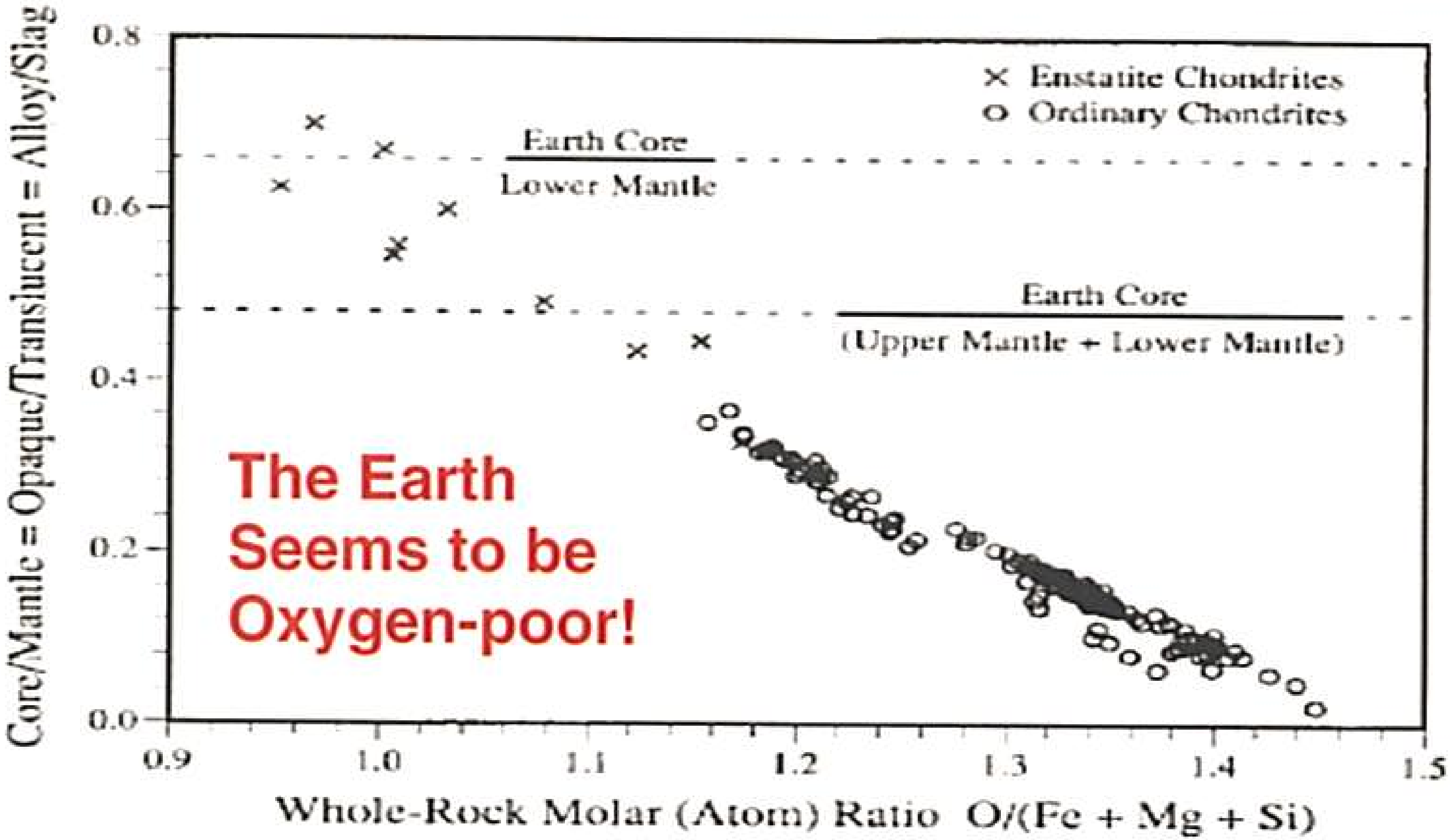
If There Were Insufficient Oxygen

- Some of the U, Th will be in **alloy and sulfide** form
- These sink as the Earth cools
- Elements with largest atomic number should sink most
- Therefore, fission fuel should sink to the center of the Earth
  - **Georeactor can form!**

Measuring the Earth's Oxidation Level

- Equate the following:
  - **Core** ⇔ **alloy & opaque minerals**
  - **Mantle + Crust** ⇔ **silicates**
- Obtain Earth's mass ratio from density profile measured with seismic data
- Compare with corresponding ratio in meteorites.
- Oxygen Content of the Earth:
  - Same as meteorite with same mass ratio as the Earth's

Evidence for Oxygen-poor Earth



Herndon, J.M. (1996) Proc. Natl. Acad. Sci. USA 93, 646-648.

^{3}He Measurements

- In air:
  - $R_A = {}^{3}He/{}^{4}He = 1.4 \times 10^{-6}$
- From deep Earth:
  - **$R \square 8 \times R_A$**
- Elevated deep Earth levels difficult to explain
  - Primordial ^{3}He and "Just-so" dilution scenarios

A georeactor naturally produces ^{3}He...

… and Just the Right Amount!

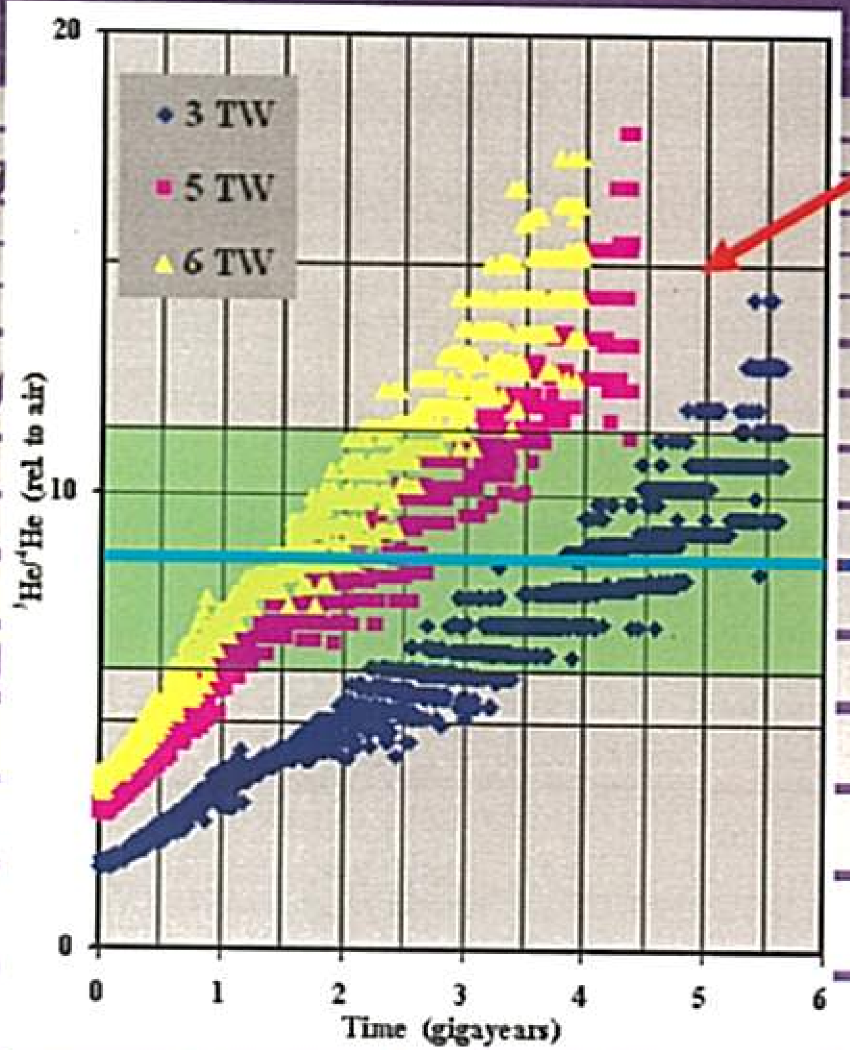


Fig. 1, J.M.Herndon,
Proc. Nat. Acad. Sci.
USA, Mar. 18, 2003
(3047)

Other Phenomena

- Georeactor as a **fluctuating** energy source for geomagnetism
- 3 of the 4 gas giants **radiate twice as much heat as they receive**
- **Oklo** natural fission reactor (remnant)

Summary of Results

- Georeactor will **NOT** be observed with KamLAND
- Large spread in background rate helps
- Low background level
  - $\Rightarrow$ Georeactor detectable with small detector

Man-made vs. Geo

- Man-made:
  - (~500 reactors) x (~2 GW) = **1 TW**
- Georeactor:
  - **3-10 TW**

If a georeactor exists, it will be the dominant source of antineutrinos!

Event Rate @ Gigaton Detector

0.0742 events/day

0.4 kton

10 TW

x 2,500,000

? 200,000 events/day

Expected rate from man-made reactors: **20,000 ev/day**

PHYSICS REPORTS (Review Section of Physics Letters) 99, No. 6 (1983) 341–396. North-Holland Publishing Company

NEUTRINO EXPLORATION OF THE EARTH*

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Received May 1983

Contents:

the machines. High-technology pump priming can induce the rebirth and revitalization of our industrial society. Nonetheless, the *raison d'être* for the construction of high-energy accelerators has always been the pursuit of science for science's sake.

We believe that future accelerators can be of direct commercial and technological importance. We envisage the construction of one (or more) large proton synchrotrons for purposes which may loosely be termed [illegible] It is the purpose of this paper to explore the nature and feasibility of such a project.

We shall refer to the accelerator dedicated to geological exploration as the GEOTRON, presumably a proton synchrotron with a beam energy [illegible] Some considerations on the construction of the GEOTRON are given in section 2. The high-energy protons must be aimed towards a distant site of geological interest. Immediately after extraction, the protons collide with a target, producing an intense and highly collimated beam of mesons. These mesons pass through a long decay tunnel, wherein they generate a neutrino beam. The complex system of proton beam transport, target, and decay tunnel must be capable of being redirected with great precision towards remote sites. We refer to this novel construction as the SNOUT of the GEOTRON. The nature of the neutrino beam which is produced at the GEOTRON complex is discussed in section 3.

The collimated neutrino beam, when it reaches the remote site to be explored, undergoes secondary interactions with the underground medium. This leads to the production of a detectable signal whose interpretation can provide useful information.

The neutrino beam can be used in at least three different ways to reveal information about the subsurface. Project GENIUS stands for Geological Exploration by Neutrino Induced Underground Sound. In this scenario, the neutrino beam is deployed at a shallow angle of declination so as to emerge from the Earth at a distant site. For example, at a declination angle of 4.5°, the point of emergence of the beam is 1000 km distant from the accelerator and its maximum depth is 20 km. As the neutrinos pass through the Earth they undergo occasional interactions wherein their energy is converted into

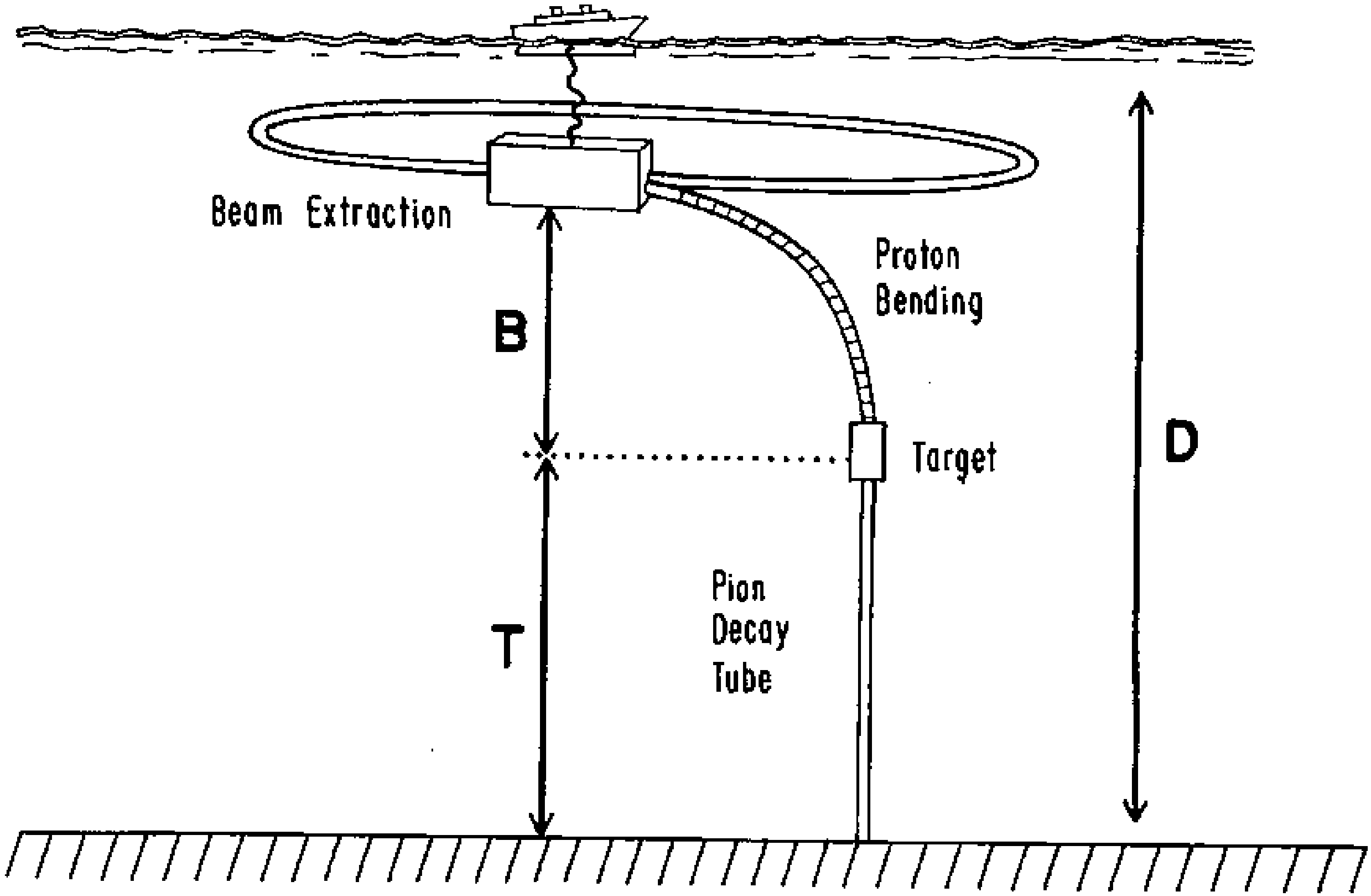


Fig. 8.3. Accelerator and beam deployment at sea, a possibility that suggests itself in a GEOSCAN Project.

Can Relic ν's be detected?

(Direct Evidence for relic ν's)

Some Preliminaries

Avg mmtm of ν's: $\langle p_\nu \rangle \sim 3.2\, T_\nu$

$\sim 5.2 \cdot 10^{-4}$ eV/c

Neutrino flux: $j_\nu \sim n_\nu \times c$ (all flavors $\nu + \bar{\nu}$)

$\sim 330\, c$

$\sim 10^{13}$ cm^{-2} sec^{-1}

$(m_\nu = 0)$.

For massive ν's: $j_\nu \sim \frac{\langle v \rangle}{c} j_0$

for $m_\nu \sim O(eV)$, $\frac{\langle v \rangle}{c} \sim \frac{\langle p \rangle}{m_\nu} \sim 5 \cdot 10^{-4} \frac{eV}{c}$

$j_\nu \sim 5 \cdot 10^{-4} j_0$

Degeneracy: If $n_\nu \neq n_{\bar{\nu}}$, $[N_p \neq N_{\bar{p}}]$

$\cdot\ n_{\nu_i} \sim \mu_i^3 / 6\pi^2$, $\bar{n}_{\nu_i} << n_{\nu_i}$

$\langle p_i \rangle \sim 3/4\, \mu_i$ & enhanced.

Proposals to detect Relic Neutrinos

- Surface effects, reflection, refraction
  enhancement by N^2?
  $\Rightarrow$ linear in G_F?

- electron spin rotation in ν sea.

- Absorption Dip in H.E. ν flux
  from $\bar{\nu} + \nu_{Relic} \longrightarrow Z$ at Resonance

- G_F^2 Volume effect to
  get acceleration on macroscopic objects.

Electron Spin Rotation

Stodolsky (1974)

- Polarised e^- moving in neutrino Background ((Campbell O'Donnell (1975))
- $e-\nu$ interaction can change polarisation.

$H_{\nu e} \sim H_{CC} + H_{NC}$

$$\langle \chi_e | H_{\nu e} | \chi_e \rangle \sim \sqrt{2} G_F \, \underline{\sigma}_e \cdot \underline{J}$$

$$\sim \sqrt{2} G_F \, \underline{\sigma}_e \cdot \underline{v}_\nu$$

- $\Delta E \sim \sqrt{2} G_F \rho_\nu |\underline{v}|$
- Need $\# \nu \neq \# \bar{\nu}$ (else vanishes)
- Let $v \sim 300$ Km/s

$m_\nu \sim O(eV)$

$\rho_\nu = n_\nu \sim 10^7 / cc$

$\Longrightarrow \Delta E \sim 10^{-32}$ eV !!

Change of Polarization direction $\delta\phi$

$$\delta\phi \sim \underbrace{(\Delta E/\hbar)}\, t$$

↳ time spent

↳ Rate of rotation

$\Rightarrow$ $\delta\phi$ in 1 year

$\sim 0.02''$ sec.

- Very Tiny Effect
- Is it Detectable?
- Need to quench earth, stray B etc
- enhancement by coherence? SC?

Volume Effect

- let $m_\nu \neq 0$
- clustering $\rightarrow$ $n_\nu \sim 10^7/cc$
- Earth motion makes ν-flux anisotropic
- ν-scattering on matter in target gives momentum transfer $\longrightarrow$ force $\longrightarrow$ net acceleration of macroscopic object $\longrightarrow$ to be detected!

Svartzmann, Zeldovich et al. (1983).

Proposal: Object (foam-like) made of small spheres of radii $a \approx \lambda\!\!\!^{-}$ (ν-wavelength); pore-size also $\approx \lambda\!\!\!^{-}$ (To avoid destructive interference) & get enhancement.

- \# atoms $N = \left(\frac{\rho}{A m_N}\right) \frac{4\pi}{3} r^3$ $(r \equiv a)$

- $$\sigma_\nu(T) = \frac{G_F^2 m_\nu^2 N^2 K^2}{8\pi} = \sigma_0 N^2 K^2$$

  - for spinless nucleus as $E_\nu \to 0$
  - for Dirac ν's
  - K depends on ν-flavor

$$K \begin{cases} = (A-Z), & \nu_\mu, \nu_\tau \\ = (3A-Z), & \nu_e \end{cases}$$

To maximise effect assume total reflection:

$$\Delta p \sim 2 m_\nu v_\nu$$

$$F = dp/dt = j_\nu \sigma_\nu \Delta p$$

& $a = F/m_T$. $\Rightarrow$ Finally

$$a \approx 10^{-23} \left(K/A\right)^2 \left(\frac{n_\nu}{10^7/cc}\right)\left(\frac{v_\nu}{10^{-3}}\right)^2\left(\frac{\rho}{20\,gm/cc}\right) \text{ cm/sec}^2$$

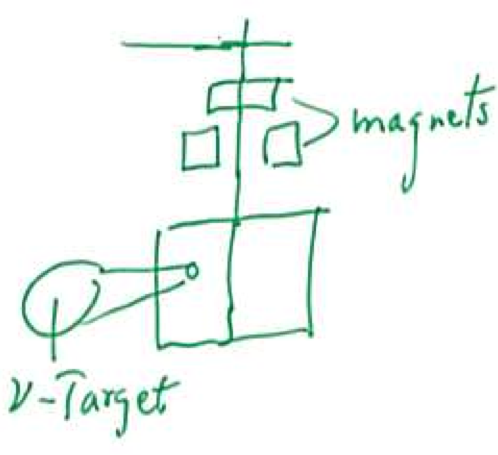
Can such small accelerations be measured?

Current best accn. measurements $\sim 10^{-13}\,\text{cm/s}^2$

Improvements possible...

Proposal Hagmann (1999)

- low T $\rightarrow$ reduce thermal noise
- use SC magnetic suspension



$\nu \bar{\nu}$ Annihilation on the Z

(Weiler 1984)

Let
- $m_\nu \sim O(\text{eV})$
- there be sources of HE ν's with $E_\nu > 10^{21}$ (eV)

On the way from source $\longrightarrow$ earth

$$\nu_{HE} + \bar{\nu}_{relic} \longrightarrow Z \quad (\text{on shell})$$

There should be an "Absorption" line in the ν-spectrum seen at Earth at E_Z:

$$E_Z \approx m_Z^2 / 2m_\nu \sim 4 \cdot 10^{21}\ \text{eV}$$

$$\sim 4 \cdot 10^{12}\ \text{GeV} \quad (m_\nu \sim \text{eV})$$

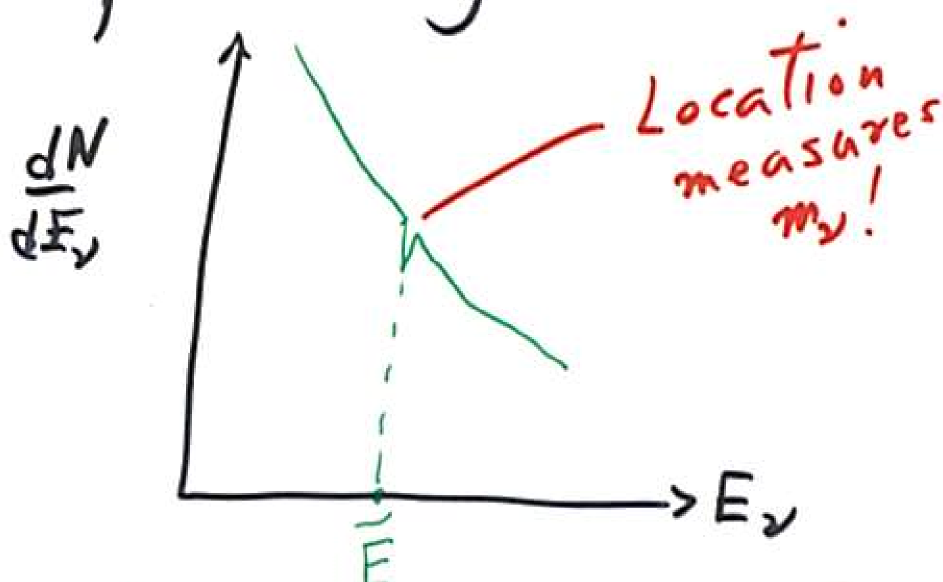
Red-shift takes $E_Z \longrightarrow \bar{E}_Z = E_Z / 1+z$

- $\sigma(\nu\bar{\nu} \to Z) = 8\pi/\sqrt{2}\, G_F m_Z^2\, \delta(s - m_Z^2)$

$$\int \sigma_\nu(Z) \frac{ds}{m_Z^2} \approx \frac{8\pi G_F}{\sqrt{2}} = 5 \cdot 10^{-32}\, cm^2$$

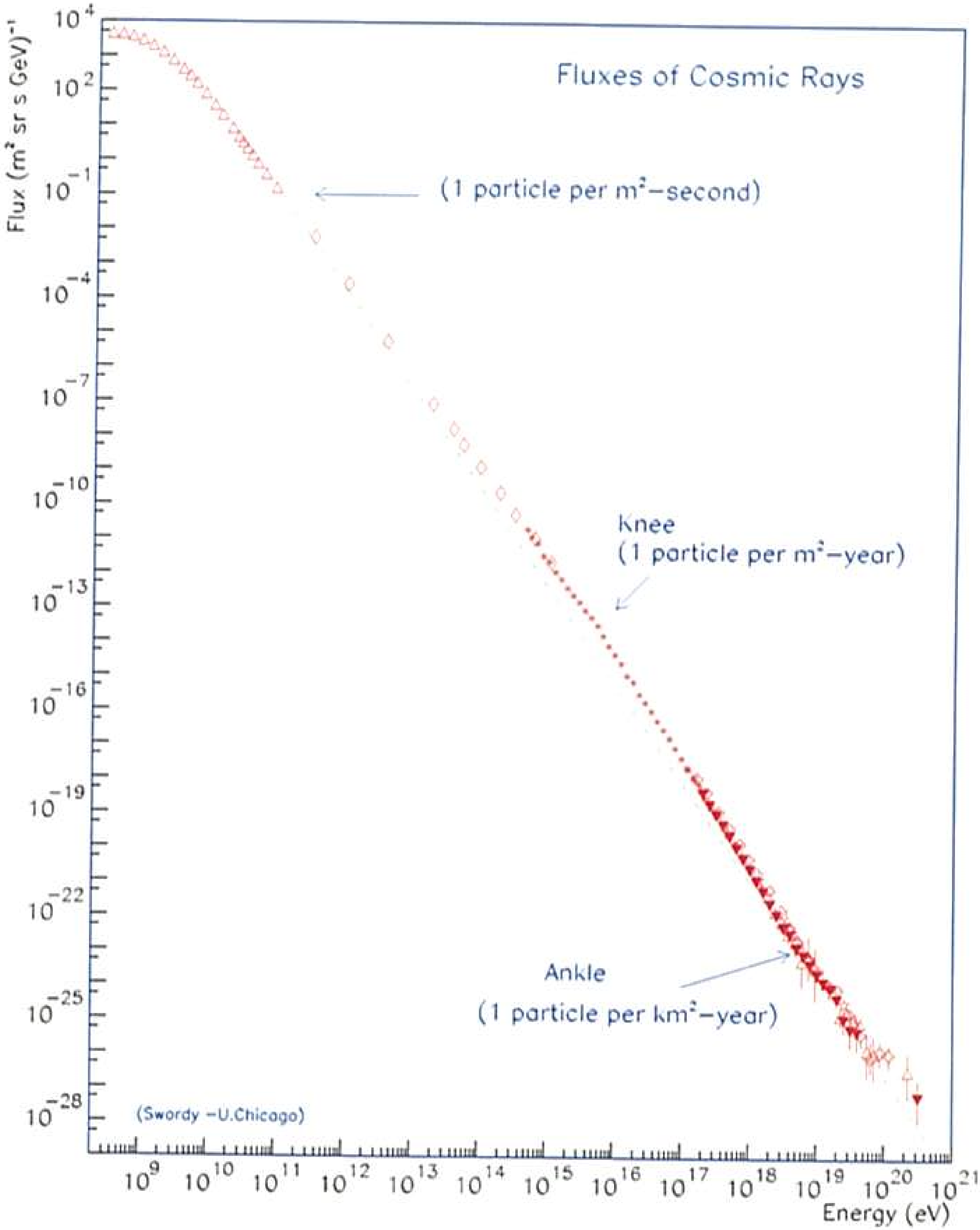
$\Rightarrow$ Need $\phi_\nu \sim 10^{-13}\, cm^{-2} s^{-1}$ for dip to be seen.

- At $R \sim 10^4$ mpc, need energy output $\sim 10^5 m_\odot / yr$
- Need many (not one) sources.
- Outlandish?
- Expected Signal:



Has this been seen already?

Cosmic Ray Spectrum



- GZK Cut-off in Cosmic Ray Spectrum

$$p + \gamma_{MBR} \rightarrow p + \pi$$

Threshold $E_{th} \sim \frac{m_\pi m_p}{E_\gamma} \sim 6 \cdot 10^{19}$ eV.

Above E_{th} mean free path $\lambda \sim \frac{1}{n_\gamma \sigma_{\gamma p}}$

$\gtrsim 10$ Mpc.

- Strong Attenuation

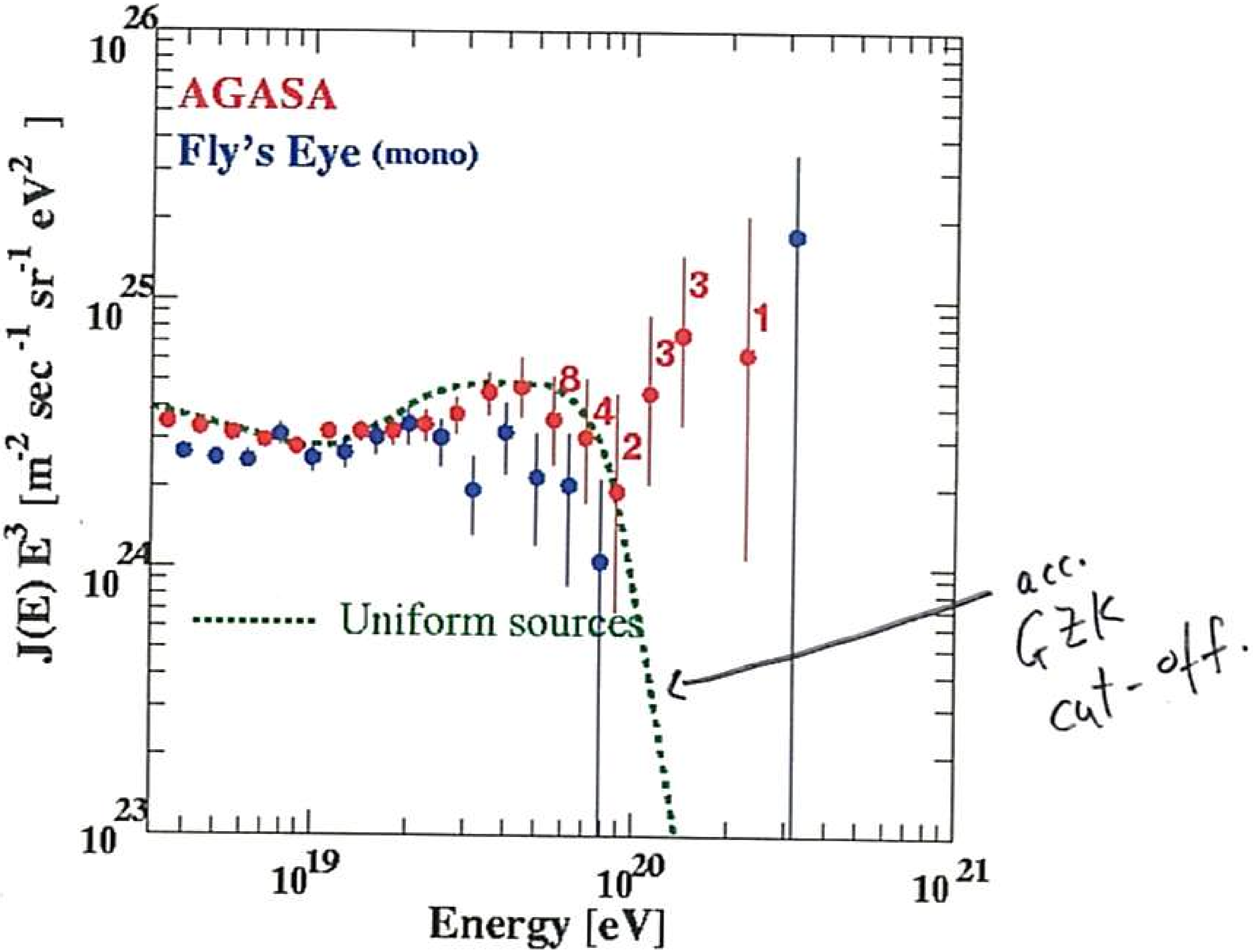
Hence CR of $E > E_{th}$ have to come from sources "nearby" & no such sources exist (AGN's etc)

But CR's of $E > E_{th}$ observed.

~ about 15-20 events. (AGASA, HIRES, ...)

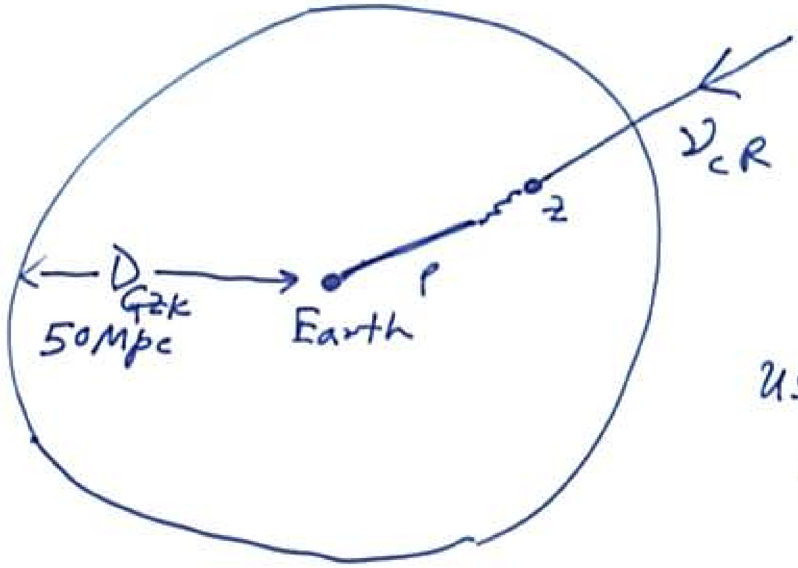
- Probably not γ-rays.
- Not ν's.
- Most probably p's.

Puzzle: What (is)/(are) the Origin?


AGASA
Fly's Eye (mono)
Uniform sources
J(E) E^3 [m^{-2} sec^{-1} sr^{-1} eV^2]
Energy [eV]
10^{26}
10^{25}
10^{24}
10^{23}
10^{19}
10^{20}
10^{21}
8
4
2
3
3
1
acc.
GZK
cut-off.

One Possibility "Z-bursts"

Weiler



$\nu_{CR} + \nu_{MB} \to Z$

$Z \to q\bar{q} \to p \ldots$

p in debris reaches us as CR with $E > E_{th}$.

- Need ν sources with enuf energy ...

Possible Tests

- Events point back to ν-sources
- New cut-off at E_{th} for Z $= 4 \cdot 10^{21} \left(\frac{eV}{m_\nu}\right) eV$.
- large γ/p ratio at E near E_{th}
- large ν flux with $E_\nu \lesssim 10^{20}\, eV$ detectable in KM3 Detectors.

If true, can measure m_ν with BG ν's!

AGENDA for NEUTRINOS AND ARMS CONTROL WORKSHOP

5-7 February 2004, Pacific Room, East-West Center, UHM Campus

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Click on the links for talks. More to come, 9 February 2004.

Time	Subject	Speaker
Thur	*5 Feb*	
0930	Introductions	John Learned, *UHM*
0940	Welcome	Dr. Charles Helsely, for UHM Chancellor Englert
0950	UH Neutrino Group Activities	Peter Gorham, *UHM*
1000	Introduction to DTRA	Arthur Wendel, *DTRA*
1030	Anti-Neutrino Detection, Earth Reactor	Gene Guillian, *UH*
1100	coffee break	
1130	Large Anti-Neutrino Detector	Franz von Feilitzsch, *TUM*
1200	Future Large Underwater Nu Telescopes	Leo Resvanis, *U. Athens*
1230	lunch break	
	Session Chair	*Steve Olsen, UHM*
1330	Monitoring Nearby Reactors	Adam Bernstein, *LLNL*
1400	Monitoring All Earth Reactors	John Learned, *UH*
1430	Science with a Low Energy Gigaton Detector	Sandip Pakvasa, *UH*
1500	coffee break	
1530	Getting Serious about Coherent Neutrino-Nucleus Scattering Detectors	Juan Collar, *Chicago*
1600	Arms Control, Monitoring and Treaty (slides, transcripts) Verification; National Tech. Means & Intell.	Richard Garwin, *IBM*
1700	Eliminating Nuclear Bombs with Ultra-High Energy Neutrinos	Hiroyuki Hagura, *KEK*
1730	Future UHE Neutrino Beams	Kirk McDonald, *Princeton*
1800	dinner *(downstairs at EWC)*	
Fri	6 Feb	
0900	*Technology Sessions: Photodetection*	*Chair: Gary Varner, UHM*
0900	Photomultipliers	Yuji Yoshizawa, *Hamamatsu*
0930	Photomultipliers	Paul Hink, *Burle*
1000	New Photodetectors	Daniel Ferenc, *UCD*
1030	Micro-Pattern Detectors	Phil Barbeau, *U. Chicago*
1100	coffee break	
1130	Adv. Flexible Circuit Mtls as Components for	Mark Richmond, *MMM*

	Particle Detectors and Other Applications	
1200	**Micromachined Large Area PMT**	**David Winn, *Fairfield***
1230	**lunch break**	
1330	*Technology Sessions: Ocean Engineering*	*Chair: Mike Peters, UHM*
1330	**Giant Deep Ocean Balloons**	**Joe van Ryzin, *MOE***
1400	**H2O and Low Cost Scintillator/Cherenkov Liquid Media**	**David Winn, *Fairfield***
1430	**Water Doping for Increased Light**	**Art McDonald, *Queens***
1500	**Coffee break**	
1530	**Cl Loaded Anti-Neutrino Detector and SN Early Warning System**	**Mark Vagins, *UCI***
1600	**Organize working groups**	***John Learned, leader***
1730	**end of session**	
1800	**barbecue *(at jgl's house)***	
Sat	**7 Feb**	
0930	**Comments**	**Richard Garwin, IBM**
1000	**Photodetector discussion**	***Juan Collar, leader***
1100	**coffee break**	
1130	**Ocean Challenges**	***Hugh Bradner, leader***
1230	**lunch break**	
1330	**Neutrino Beams**	***Kirk McDonald, leader***
1500	**coffee break**	
1530	**Summary and Plans**	**All**
1630	**End of Workshop**	

arXiv:hep-ph/0305062 v2 29 Jun 2003

Destruction of Nuclear Bombs Using Ultra-High Energy Neutrino Beam

— dedicated to Professor Masatoshi Koshiba —

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Abstract

We discuss the possibility of utilizing the ultra-high energy neutrino beam ($\simeq$ 1000 TeV) to detect and destroy the nuclear bombs wherever they are and whoever possess them.

Neutrinos and Arms Control: Thinking Big about Detection of Neutrinos from Reactors at Long Distances

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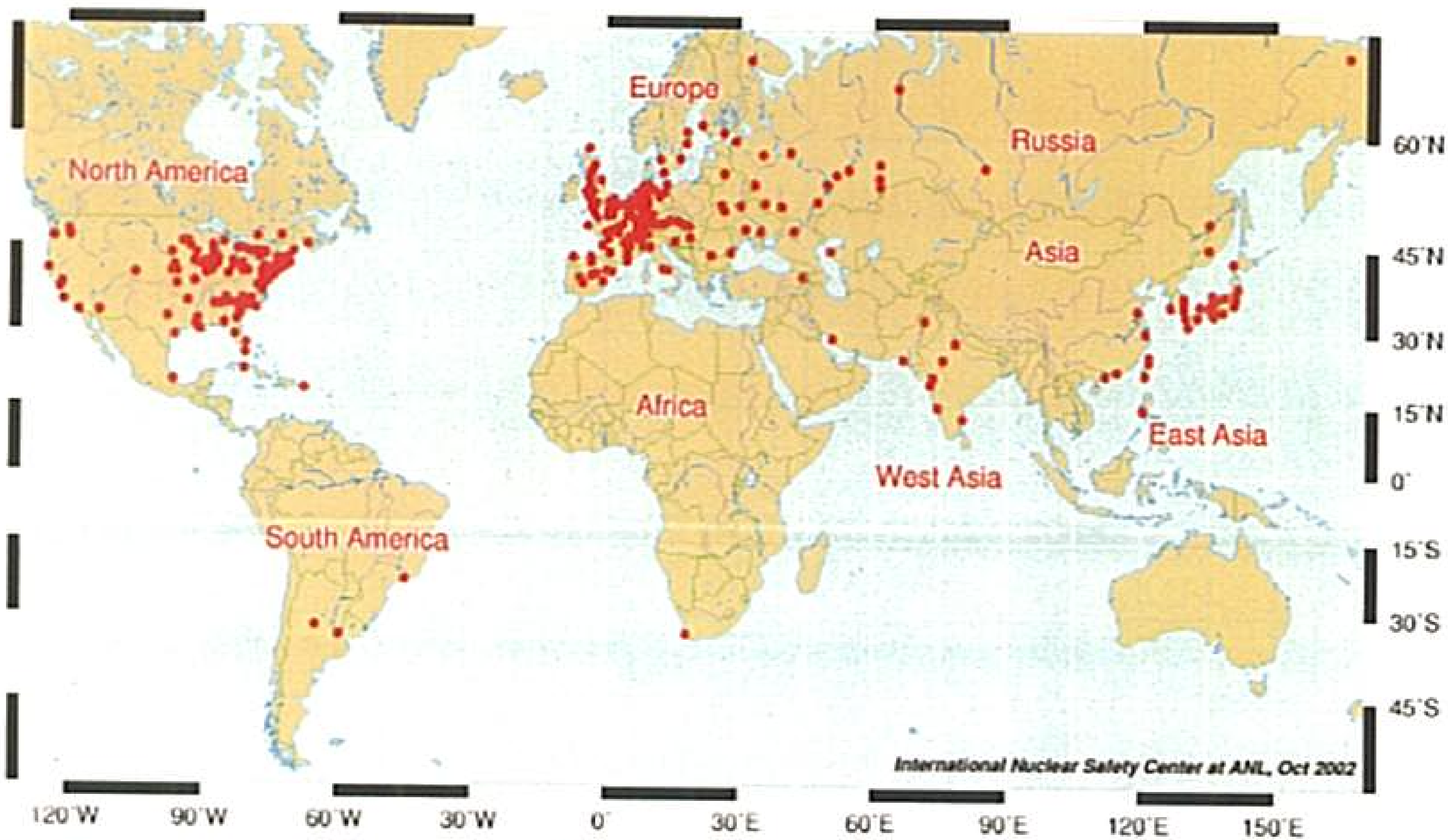
ABSTRACT

We discuss a somewhat futuristic plan for a world network of enormous neutrino detectors, which may be employed for monitoring the activity of all reactors on earth. Three (or more) cubic-kilometer size instruments with sensitivity down to about 1 MeV, placed in the deep oceans (or possibly lakes) can record the electron anti-neutrino fluxes from reactors, no matter where they reside. Using known power levels from the roughly 440 operating reactors, one can detect and monitor any new reactor, in particular one which may be producing illicit nuclear weapons material. Such a signal cannot be hidden or jammed, and via tomography may be located to a precision of order 20 kilometers over a one year timescale.

The suggested array would have many ancillary applications, ranging from detection of nuclear bomb tests, to studies of neutrinos from supernovae from throughout our supercluster and seeking the decay of protons to significant levels. First estimates are that such an array of detectors, after industrial development particularly in the area of photodetectors, could cost in the range of a new particle physics accelerator or an aircraft carrier.

World Reactors



Directionality?

- Inverse beta not inherently directional.
- Weak correlation between neutrino and direction from positron annihilation and n capture. Probably not useful.
- Can we use electron scatters? Needs study.
- Main method, **tomography** using known counting rates and at least three stations around the world.

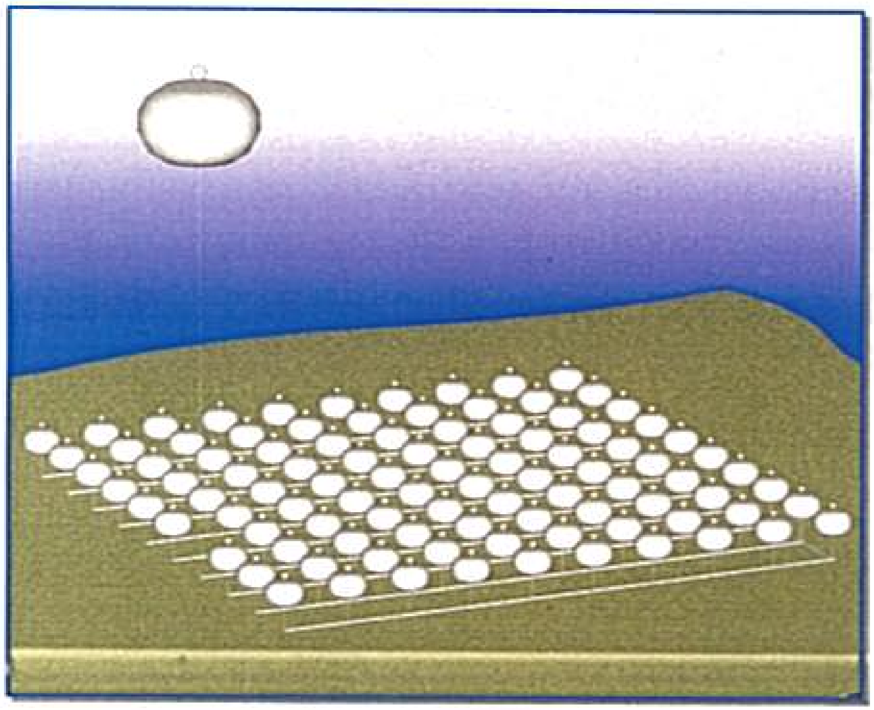
Tomography

- Most power reactors well known (1-2%, maybe better) in output as function of time, day by day at least (IAEA).
- A new unknown reactor (2GW) will contribute average of 43 counts/day at 6000km.
- Pin down location to ~20 km in one year.
- Need numerical simulations to study resolution and detector siting. First, naïve example follows.

Design Concept

- Must use water, nothing else affordable.
- Use pure water, for acceptable backgrounds.
- Possibly load with low ^{40}K salt: not expensive, helps neutron detection and 3% buoyancy of seawater.
- Place in deep ocean for low rates and mobility. Mine based detectors not affordable.

Array Sketch



- Ocean bottom array, 4 km x 4 km
- Alternative may be distributed array (to get gradient along array). Line? Triangle? Around world?

Detection of Nuclear Explosions?

- Beauty of this method is that neutrinos cannot be faked, jammed or shielded.
- Detection measures weapon yield.
- Certainly can detect 100 kT device out to >1000 km => 2000 counts.
- Need studies to see what can be done employing info from three arrays.

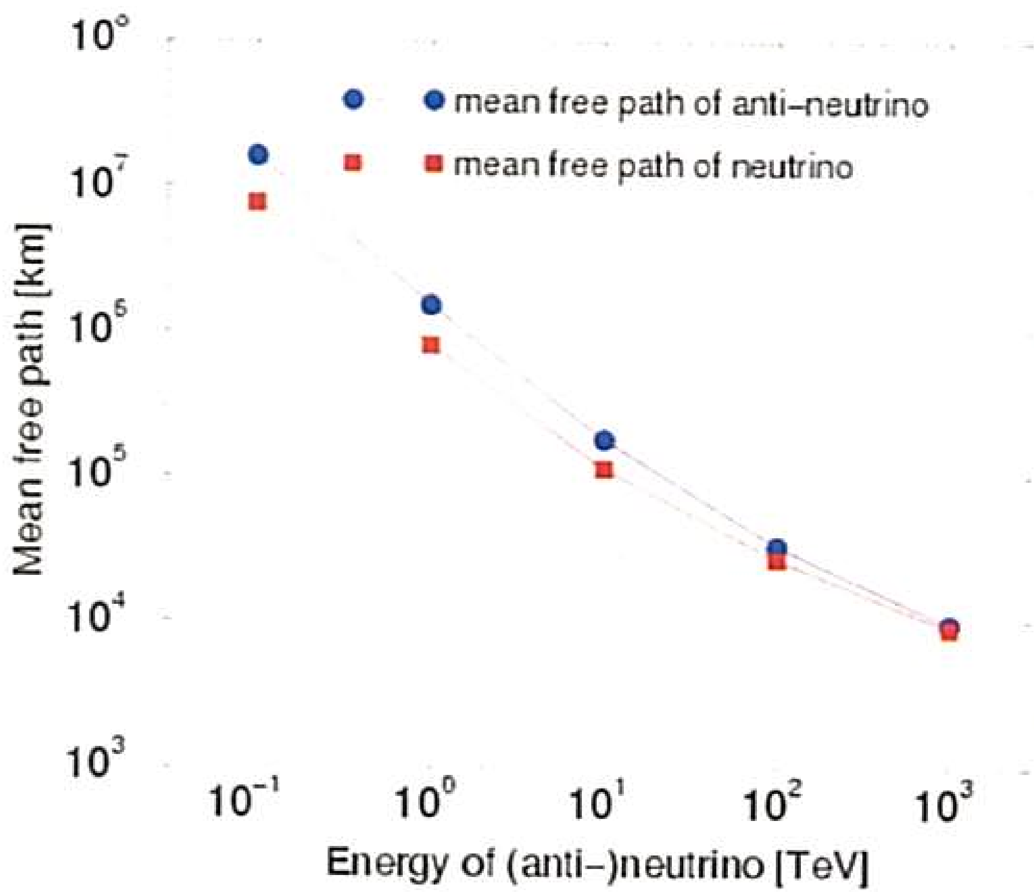
Summary: A New Option for Arms Control Monitoring

- A 1 km^3 - 2 MeV anti-neutrino detector in deep ocean is certainly possible, question is economics and scaling… first cut indicates it may be on $10B scale.
- Significant optical detector development needed, plus other studies.
- Would allow monitoring of ALL world's reactors on a daily basis, plus detection and location of new reactors to few tens of km.
- Can detect some nuclear explosions.
- Huge pure scientific program and community. involvement: high spinoff in science and technology.

Introduction

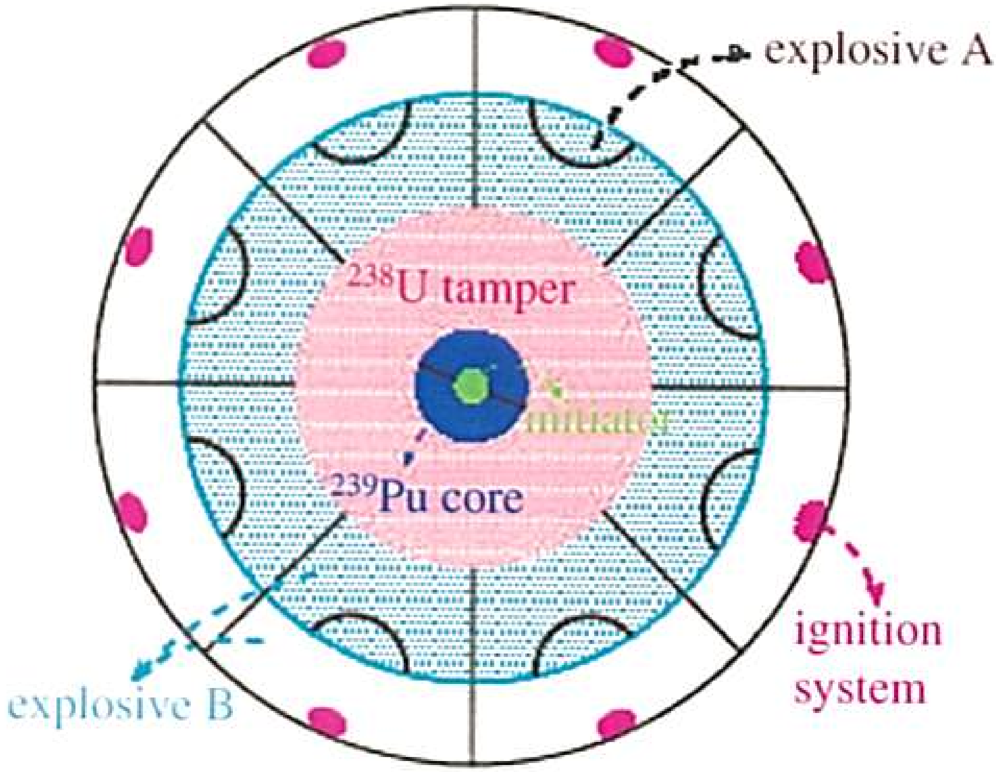
- Non-proliferation of nuclear weapons is difficult at present in spite of the existence of NPT.
- Detecting nuclear bombs globally and eliminating them safely are very important for global security.
- Interestingly enough, neutrino is considered to be the only particle that is capable of doing that on the global scale.
- Big collaboration of particle, nuclear, reactor and accelerator physicists and security experts will play an essential role for the purpose.

Mean free paths of neutrinos



- Calculated at the tree level
- Only two flavors (u and d quarks) are included
- Scaling functions with no QCD corrections
- No neutrino oscillation is assumed
- Protons and neutrons are uniformly distributed inside the Earth
- If one includes several effects, the cross-sections will become a few times larger, leading to smaller mean free paths

What is a nuclear weapon?

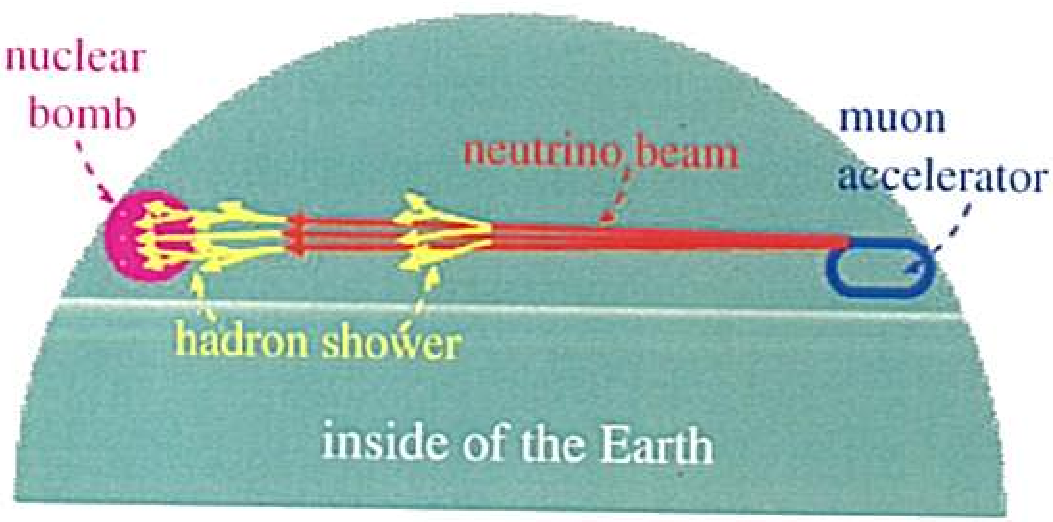


1. Ignition by explosives
2. Shock wave is created, density wave makes ^{239}Pu and ^{238}U go beyond the critical point
3. Initiator gets broken (aluminum foil)
4. In 10^{-6} sec super-critical fission reaction occurs everywhere in the core
5. Tamper works to suppress the "fizzle explosion"
6. Full explosion produces a bomb yield of ~20 kt

How to eliminate them from the other side of the Earth?

$E_\nu \sim 100 - 1000$ TeV

mean free path = diameter of the Earth



① Hadron shower hits the target bomb and causes sub-critical nuclear fissions

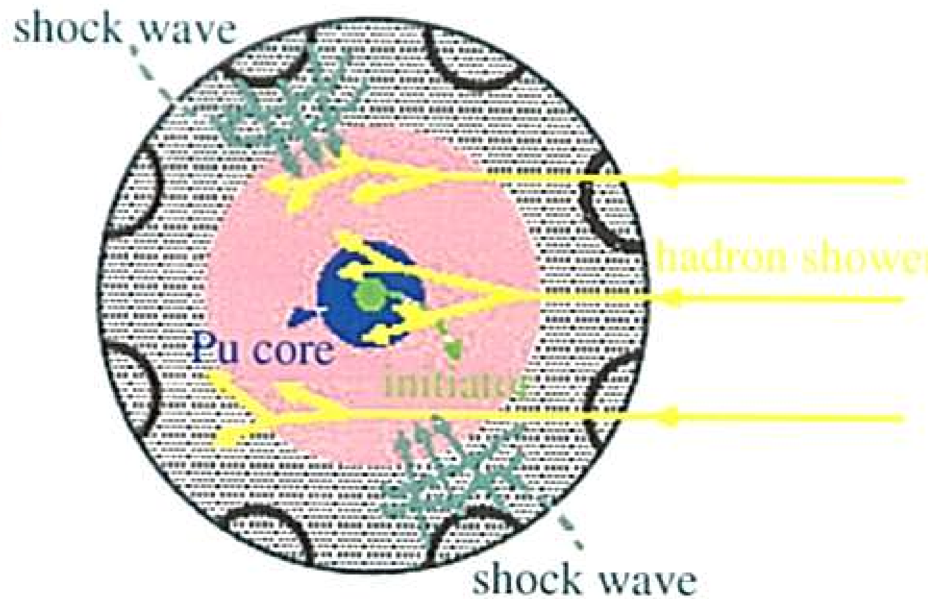
② The temperature of the bomb increases

③ Above 250 degrees the surrounding explosives (dynamite) get ignited

④ The rest of the process is the same as the `ordinary' nuclear bomb explosion

The important difference!

1. The bomb is exposed to hadron beams which play the role of initiator.
2. The beams cause sub-critical chain reactions to start before the shock wave reaches the center
3. Such a phenomenon is well known as the ``fizzle explosion''
4. This makes the destruction of the nuclear bomb relatively safe.



What are the required parameters?

According to the theory of ``fizzle explosion'', we have obtained the following values:

- 10^{16} fissions per 10 kg of ^{239}Pu to reach 300 degrees.
- 10^{19} fissions per 10 kg of ^{239}Pu to vaporize all the plutonium. This is needed when the plutonium is stored away from the explosive material.

We can calculate numerically how many neutrinos are needed to reach the values in a given time.

Numerical results – tentative

Using three MC programs, that is, HERWIG6, MARS and MCNPX, we have obtained:

- For E_ν = 1000 TeV neutrinos, the required number of neutrinos is 10^{14} in a few seconds.
- For lower-energy neutrinos, we will need more larger intensity.

Is it practical to do so?

Number of questions

1. Can we steer the beam?
   $\Delta\theta \sim 10^{-7}$ (rad)
   => Not easy but possible
   Current achievement $\Delta\theta \sim 10^{-6}$ (rad)
2. Can we make 10^{14} neutrinos in a short period, for example, in ~1 sec?
   => High-intensity proton machine (now $\sim 10^{13}$ /sec)
3. Can we make a 1 PeV machine?
   => The hardest problem (now ~1-10 TeV)

Conclusions

- UHE neutrinos can be very useful:
  - Global disarmament
  - Earth tomography (`X-ray' by neutrino)
  - Perhaps communication (a prototype of SETI)
- Technology development:
  - Invention of much stronger magnet ~10-100 Tesla
  - High-energy, high-intensity accelerator
  - Fine alignment
  - Detection of nuclear bombs (J. Learned)
- Financial support:
  - Massive investment (~$50B) will be needed
  - World-wide collaboration

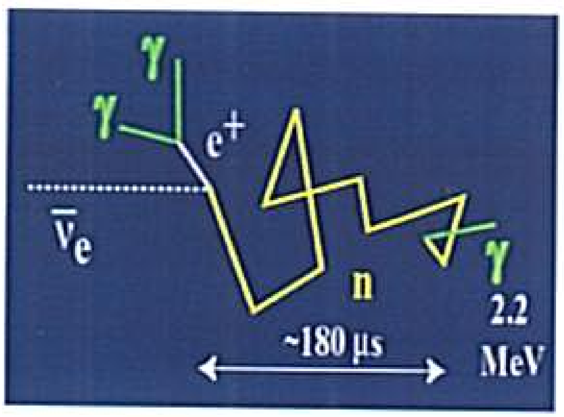
Goal: Detect Reactors from Whole Earth

- Need ~1 gigaton = **1 km³, ~1 MeV sensitivity**

reaction process : inverse- β decay ($\bar{\nu}_e + p \longrightarrow e^+ + n$)

$n + p \longrightarrow d + \gamma$

distinctive two-step signature



$$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806\ MeV$$

- prompt part : e^+

  $\bar{\nu}_e$ energy measurement

  $$E_\nu \sim (E_e + \Delta)[1 + \frac{E_e}{M_p}] + \frac{\Delta^2 - m_e^2}{M_p}$$

  $$\Delta = M_n - M_p$$

- delayed part : γ (2.2 MeV)

- tagging : correlation of time, position and energy between prompt and delayed signal

Rate

- Scale rates from KamLAND measurements.
- R ~ (832/day)(P/1GWt)(10^3km/D)^2(V/1km^3)F(E,D/E)

  F(E,D/E) ~ 0.5 – 1.0 to account for oscillations
- If deep (> 4km water equiv), little background.

Sum of All Reactor Power

- Total of 440 power reactors, 2GWt/reactor
- 2574 TWe-Hrs in 2002, equiv ~0.881 TWt
- Rate in km^3 about 17,000 nuebar/day
- 1 σ ~ 130/day, measure to 0.77%/sqrt(days)
- Typical reactor 1000 km away, 1543 cts/day implies about 12 σ measurement each day!

(Obvious) Shopping List

- Probe Nucleon Decay to new levels (p-decay, n-$\bar{n}$ ann...)
- Time Variation (Day-Night) in Solar Neutrinos
- Detect Supernova (Type II) upto Virgo Cluster
- Measure Relic SN $\bar{\nu}_e$'s
- Neutrino Astronomy (Point Sources of E_ν = MeV to PeV)
- Obvious Candidate for Far Detector for ν-Factories
- High Energy ν's from Dark Matter Annihilation (earth, sun, galaxy)

- Search for natural geo-reactors such as "Oklo" (e.g. at centre of earth), (via $\bar{\nu}_e$'s)

- Detailed study of distribution of U & Th in earth (providing heat flow) by $\bar{\nu}_e$ emission.

- Cosmic Ray studies of origin & composition

- Geophysics in study of earth density

- ν - SETI. (Search for ν's at 45 GeV $= \frac{1}{2} m_Z$)

CONCUSIONS

Neutrinos are alive & well.
We are entering Neutrino Century
& will keep busy • learning about ν's
& • learning to use them.