INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.858 - 40

III

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

12 June - 28 July 1995

NEUTRINO PHYSICS

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Please note: These are preliminary notes intended for internal distribution only.

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LECTURE 3 (Smirnov)

Last lecture we have derived the evolution equation for the eigenstates of the Hamiltonian: (ν_{1m}, ν_{2m})

$$i\frac{d}{dt}\begin{pmatrix}\nu_{1m}\\ \nu_{2m}\end{pmatrix} = \begin{pmatrix}H_{1m} & i\dot{\theta}_m\\ -i\dot{\theta}_m & H_{2m}\end{pmatrix}\begin{pmatrix}\nu_{1m}\\ \nu_{2m}\end{pmatrix}$$

where ~~the ...~~

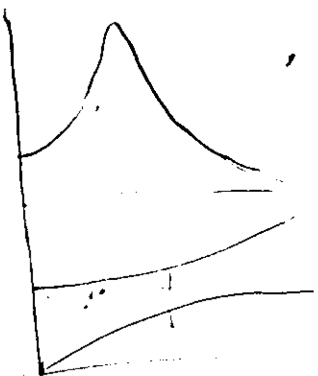
θ_m and H_{1m} H_{2m} are determined from diagonalization of the H.

$$\vec{\nu}_f = S(\theta_m)\vec{\nu}_m$$

$$\tan 2\theta_m = \frac{\sin 2\theta}{\cos 2\theta - 2\sqrt{2}\, G_F \frac{E n_e}{\Delta m^2}}$$

$$H_{2m} - H_{1m} = \frac{\Delta m^2}{2E}\sqrt{\left(\cos 2\theta - 2\sqrt{2}G_F\frac{E n_e}{\Delta m^2}\right)^2 + \sin^2 2\theta}$$

resonance:



splitting is minimal.

ADIABATICITY CONDITION =

$$\boxed{\frac{H_{2m} - H_{1m}}{\dot{\theta}_m} \equiv x \gg 1}$$

Physics. $\cancel{\theta}$ if the condition is fulfilled: one can neglect $\dot{\theta}_m$

$\Rightarrow$ the equation for ν_{im} is diagonalized

$\nu_{1m} \not\Leftrightarrow \nu_{2m}$.

- A.C. is the most crucial in resonance:

$\Rightarrow$ smallest splitting $H_{2m} - H_{1m}$

explicitly.

$$x_R = \frac{\Delta m^2}{2E} \frac{\sin^2 2\theta}{\cos 2\theta \left(\frac{1}{n_e}\frac{dn_e}{dx}\right)}$$

$$P \sim e^{-\frac{\pi}{2} x_R}$$ Landau Zener

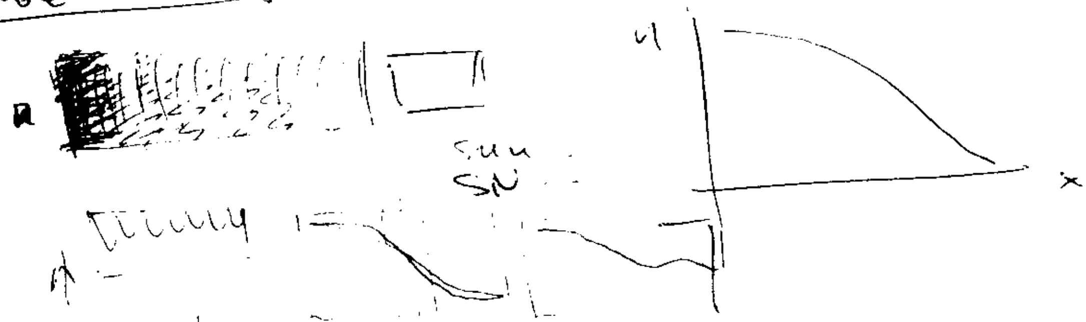
- $x_R \downarrow$ $E \uparrow$ with increase of E the adiabati becomes worse
- $x_R \uparrow$ $\sin^2 2\theta \uparrow$

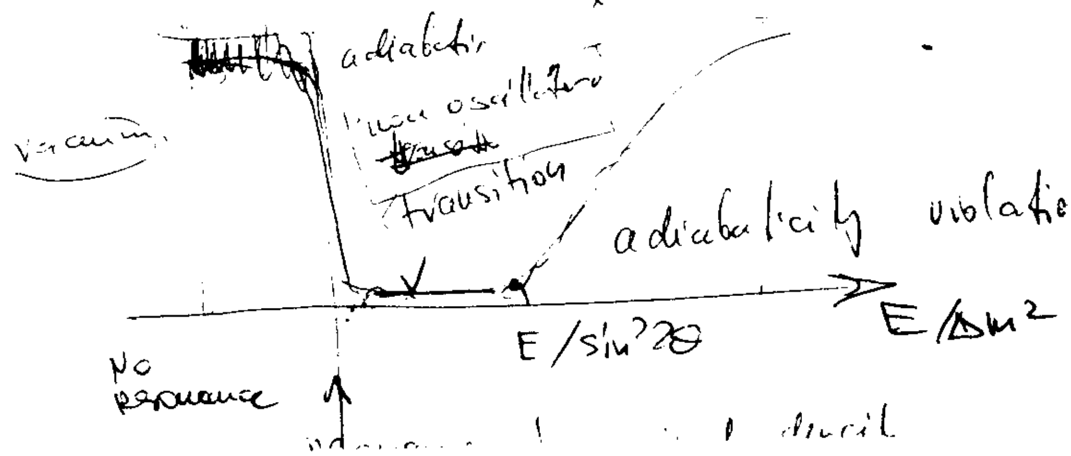
ENERGY DEPENDENCE OF EFFECTS:

Depth of oscillation, $\sin^2 2\theta_m$ depends on Energy

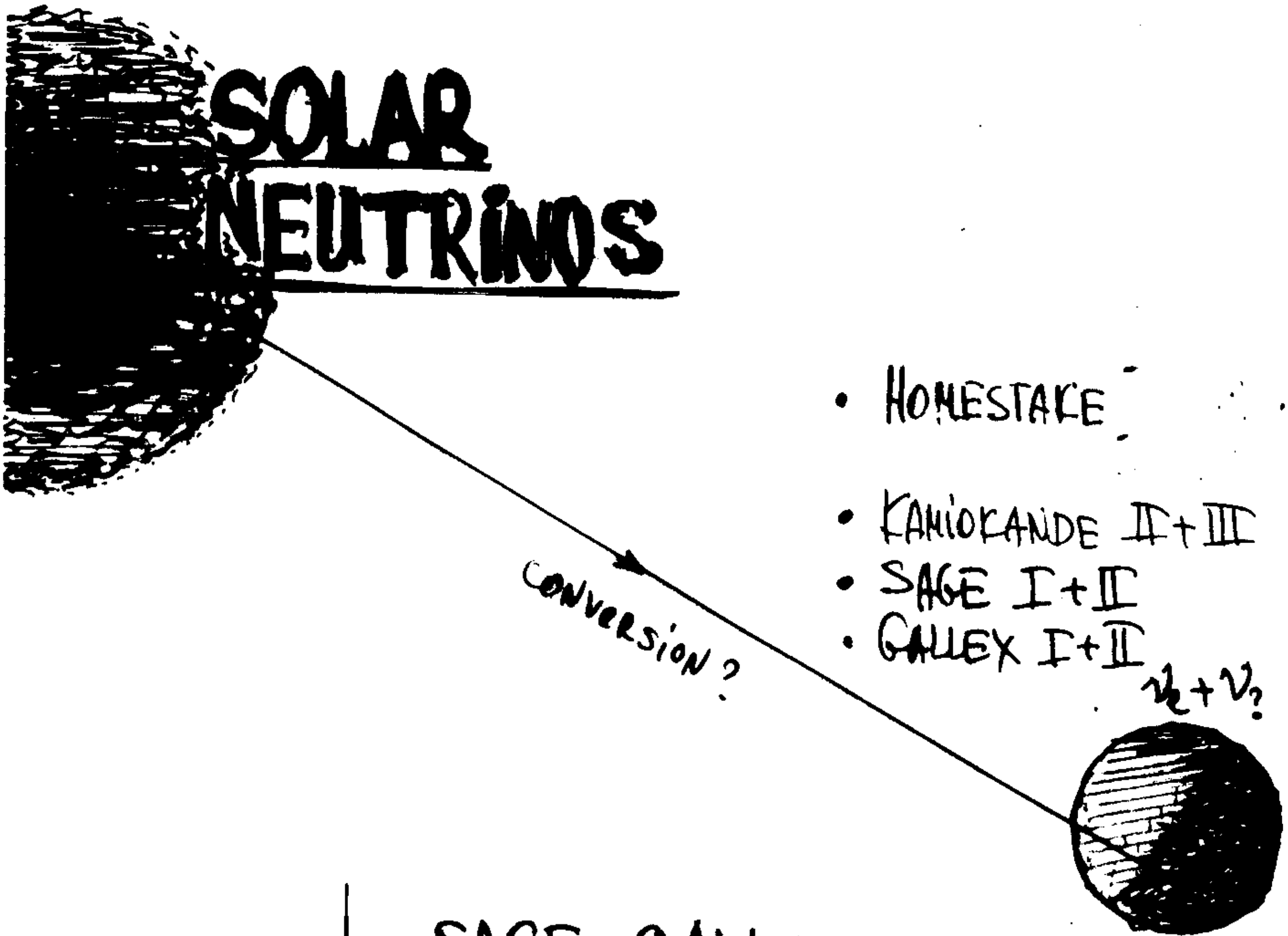
Earth is a good example

Variable density

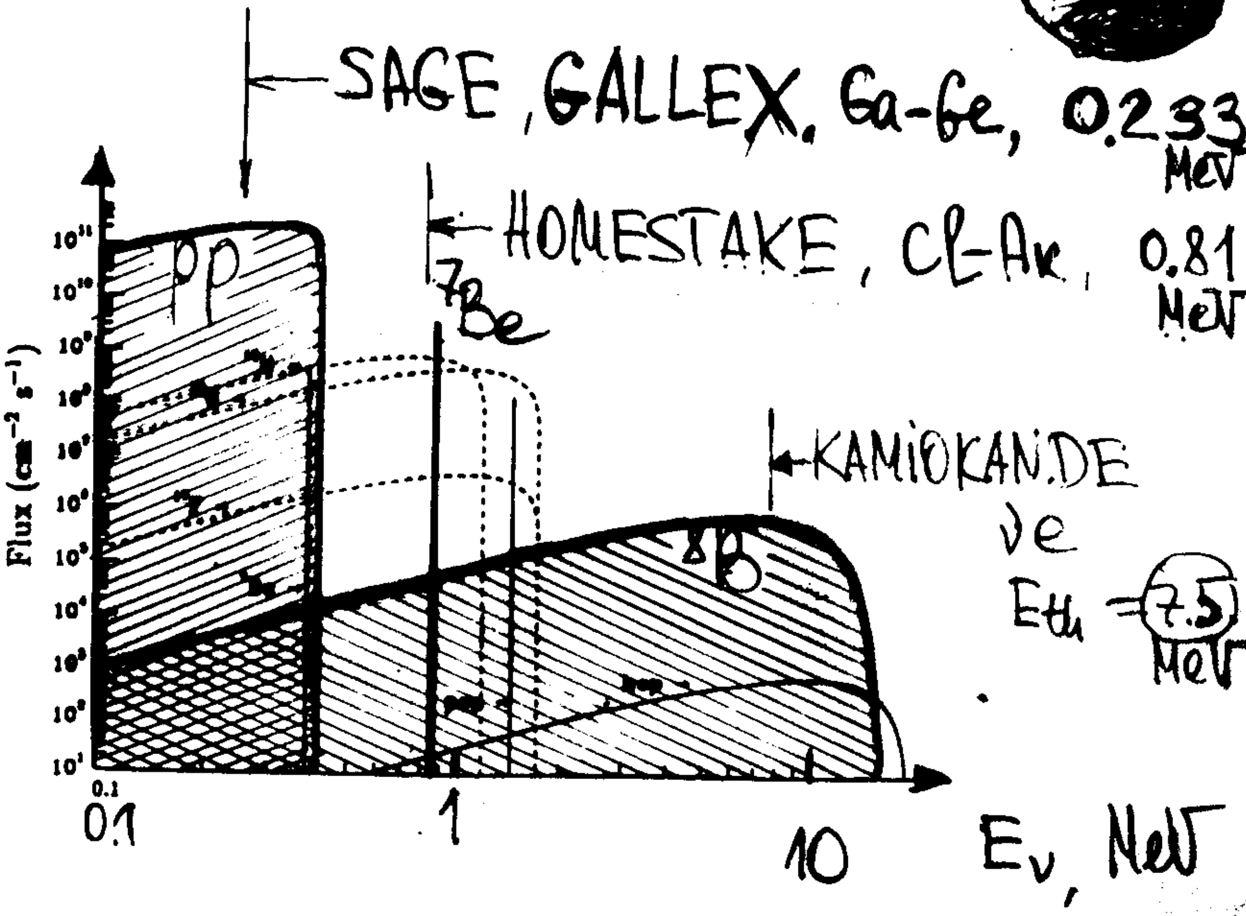




SOLAR NEUTRINOS

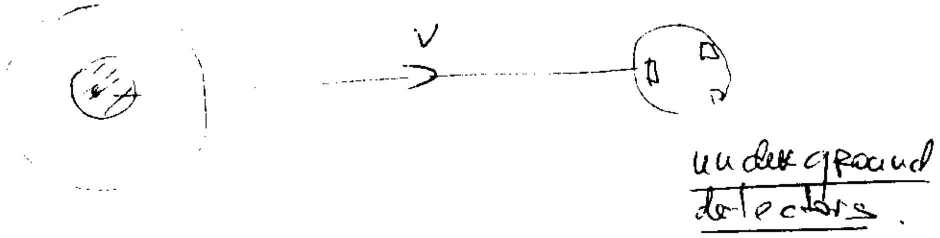


- HOMESTAKE
- KAMIOKANDE II+III
- SAGE I+II
- GALLEX I+II



HINTS

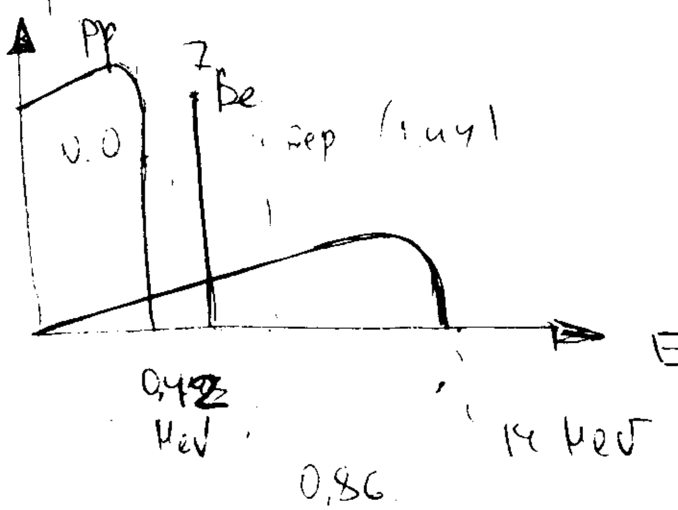
SOLAR NEUTRINO PROBLEM



- central region of the Sun in the source of ν_e
- chain of reactions = Burning of H → He
  in each chain ≈ 2ν

  pp - cycle , CNO small.

- Energy spectrum.



check

Exp	E_{th} MeV
Homestake	0,81
Kamiokand	7.
GALLEX SAGE	0,233

- 4 detectors ⇒ have different thresholds

sensitive to different part of $\nu_\odot$ spectra → spectroscopy

SOLAR NEUTRINO problem.

Main question:

what is the origin of disagreement of data and predictions?

astrophysics (predictions of SSM) ← → properties of neutrinos → physics beyond the SM

Main problem:

- uncertainties in predictions of fluxes (still big)
- correctness of the Exp. data

RESULTS: ?

THREE PHASES OF THE SOLAR NEUTRINO PROBLEM:

1. "THEORY WITHOUT experiment".
   B. Pontecorvo: (before any exp. data) oscillations can diminish ν_e-flux.

2. "THEORY AND EXPERIMENT"

   ~ 20 years.

   Bahcall SSN predictions > Davis' Experiment Result

   source of disagreement?

Main problem uncertainties in the predict

3. "Experiment without theory"

   - Rather precise data from four experiments
   - Kamiokande is calibrated.
   - GALLEX Ex experiment with artificial source.

Important aspects of the problem can be formulated in (almost) solar model independent way.

Experimental DATA

Homestake experiment

(terminated in autumn '94)
~130 Runs.

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

$E_{th} = 0.81$ MeV

method: counts the number of Ar atoms

measure: Ar - production rate Q_{Ar}

units: SNU. 1 SNU: when 1 atom is produced per 1 sec in 10^{36} atoms of the original isotope.

Result

$$Q_{Ar}^{exp} = (2.55 \pm 0.17 \pm 0.18)\ \text{SNU}$$

theory.

$$Q_{Ar}^{SSM} = 9.3\,{}^{+1.3}_{-1.4}\ \text{SNU}$$

(Bahcall Pinsonneault)

$$R_{Ar} = \frac{Q_{Ar}^{exp}}{Q_{Ar}^{the}} \simeq 0.27$$

Time variations ?

KamioKANDE

$\nu e \to \nu e$. · $E^{th} = 7 - 7.5$ MeV (only Boron neutrinos)

measure the recoil electrons by Čerenkov radiation

- Direction
- ENERGY

$$F_B = \left(2.75 \,{}^{+0.20}_{-0.18} \pm 0.41\right) \cdot 10^6 \, cm^{-2} \cdot s^{-1}$$

$$F_B^{th} = 6.6 \left(1 \,{}^{+0.14}_{-0.17}\right) \cdot 10^6 \, cm^{-2} s^{-1}.$$

$$R_{\nu_e} = \frac{F_B}{F_B^{SSM}} = 0.417 \,{}^{+0.30}_{-0.27} \pm 0.062$$

No time variations
No Distortion of energy spectrum } within the ERROR bars.

There is another important result:
new limit on $\bar{\nu}_e$ flux from the Sun.

$$F < (2-4)\cdot 10^{4}\ cm^{-2}\,s^{-1}$$

$$\frac{F_{\bar{\nu}}}{F_{\nu}^{SSM}} = (3-6)\cdot 10^{-3}.$$

$\bar{\nu}_e$ can be formed as it if neutrinos have magnetic moment.

$$\nu_e \xrightarrow{\text{spin-flip}} \bar{\nu}_\mu \xrightarrow{\text{oscillations}} \bar{\nu}_e$$

C

SAGE. GALLEX.

$$\nu_e + {}^{71}Ga \to {}^{71}Ge + e \qquad E^{th} = 0.233\ MeV$$

Radiochemical.
⇒ count the number of produced atoms ^{71}Ge

germanium production rate Q_{Ge} (SNU)

SAGE (31 extraction):

$$\boxed{Q_{Ge}^{exp} = \left(69 \pm 10 {}^{+5}_{-7}\right)\ SNU}$$

GALLEX (39 extraction)

$$\boxed{Q_{Ge}^{exp} = \left(77 \pm 10 \pm 6\right)\ SNU}$$

& ?

Theory:

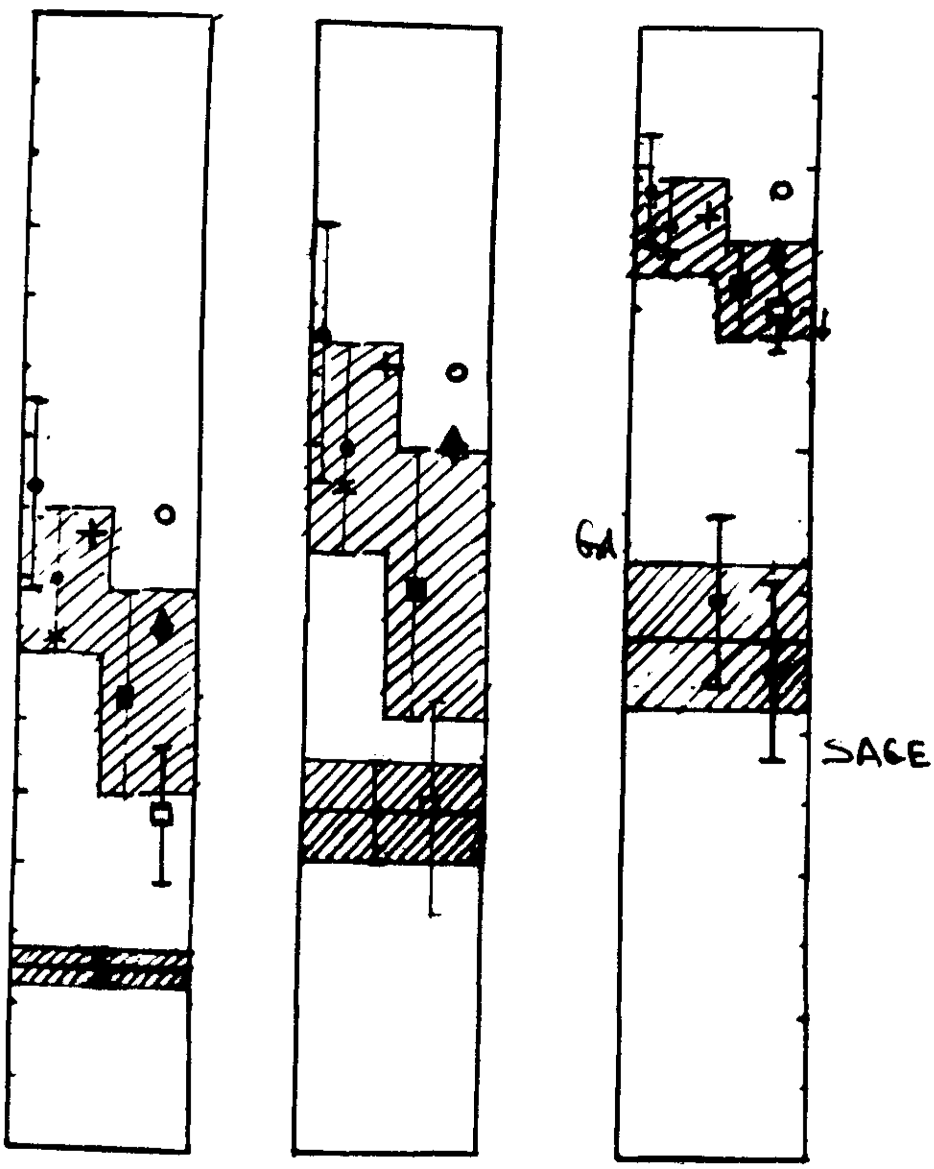
$$Q_{Ge}^{SSM} = 137 {}^{+8}_{-7}\ SNU$$

(BP-95)

$$R_{Ge} = \frac{Q_{Ge}}{Q_{Ge}^{SSM}} = \underline{0.53}$$

23.

Data vs. predictions



Cl-Ar   Ve   Ga-Ge

Profitt

"1995"

Bahcall - Pinsonneault × (without diffusion) 199

with diffusion

Turck-Chieze Lopes 1993

Dar-Shaviv 1994

Berthomieu et al 1993

+ Castellani Degl'Innocenti Fiorentini 1993

Problem 7.

THEORetical uncertainties:
THE most important:

inside the Sun ① $^7Be + p \rightarrow {}^8B + \gamma$ — cross section?

$\rightarrow$ ν_B BORON neutrinos.

$S_{17}(0)$ can be 25% below BP-95 used.

$F_B \downarrow 25\%$.

② Collective plasma effect.

$T_c \downarrow 2\%$ $F_B \downarrow 25\%$.

$\Rightarrow$ These uncertainties are enough to explain the Kamiokande result. !

But
Homestake
&
Gallium experiment
are not explained!

"SOLAR ν-problem
without ~~[illegible]~~ ⊙-model"

= model independent analysis:

- general notion about ν-spectrum
  but now the absolute values of fluxes.
- Absolute values of fluxes → free parameters
  to be found from $\nu_\odot$ experiment
- confront the data ~~[illegible]~~ from different
  experiments immediately
- use ~~[illegible]~~ solar luminocity normalization
  condition.

Two key points
OF ANALYSIS

① KAMIOKANDE versus HomeStake:

Kamiokande Flux. F_B^{exp}

gives $Q_{Ar}^B \simeq (3.00 \pm 0.45)$ SNU

which exceeds the total Cl- signal:

$$\boxed{Q_{Ar}^B(\text{Kam}) > Q_{Ar}^{exp}}.$$

- ~~[illegible]~~
  Be ~~the~~ neutrino flux should be strongly
  suppressed (as well as pep, NO).

1st statement → • something contribute to Kam. but not
  to Homestake

,

II Gallium Results vs Solar luminosity

Cycle: result of chain:

$4p + 2e^- \rightarrow {}^4He + 2\nu_e + Q$. 26 MeV

If the Sun in termal equilibrium:

$L_\odot = E_N - L_\nu$

pp- neutrinos give main contribution:

$$F_\nu \simeq 2 \cdot \frac{L_\odot}{Q - \bar{E}_\nu}$$

number of change per second

$\boxed{Q_{pp} \simeq 71 \text{ SNU}}$

∴ Signal in Ga experiment ~~are~~ at the level of ~~the~~ signal from pp ν flux which follow from the luminocity of the sun!

Contribution from B- neutrinos, as measured by Kamiokande ≈ 7 SNU.

~~over~~ "minimal" signal: $71 + 7 = \underline{78 \text{ SNU}}$

∴ ~~all~~ Contributions from all other fluxes should be suppressed.

In particular Be - neutrino flux which contribute to $Q_{Ga}^{Be} \sim \underline{37-38}$

Homestake vs. Kamiokande

Gallium versus $L_\odot$

strong suppression of F_{Be}

$\frac{F_{Be}}{F^{SSM}_{Be}} < 0.4$ (2σ)

~~[illegible]~~ impossible to explain by astrophysics

astrophysical solutions are excluded

Be-neutrinos ? central problem?

$\boxed{\text{BOREXINO}}$

approved

Very easy to find the fluxes which give best fit of the data

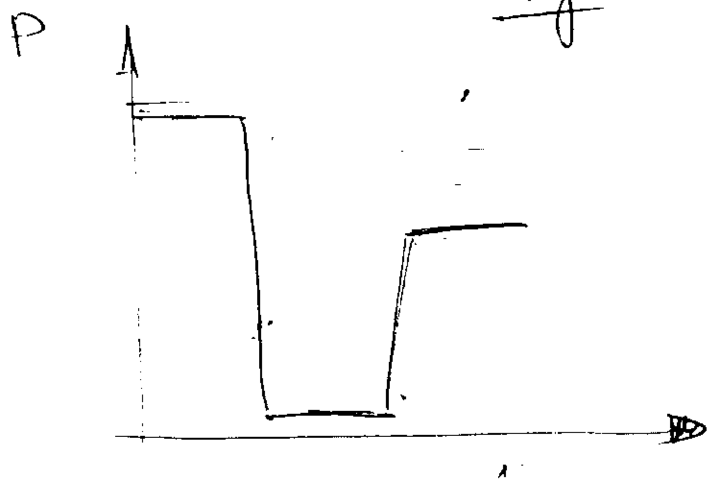
(1) $F_B \sim 0.4\, F_B^{SSM}$

(2) F_{Be} $F_{N,O}$ F_{pep} → are strongly suppressed

(3) F_{pp} is unsuppressed or very weakly suppressed

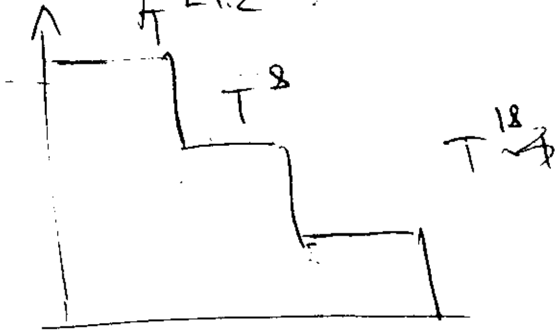
↓

allows to trace the energy dependence of suppression

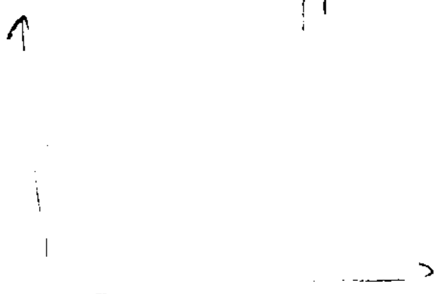


SOLUTIONS

① Astrophysics:



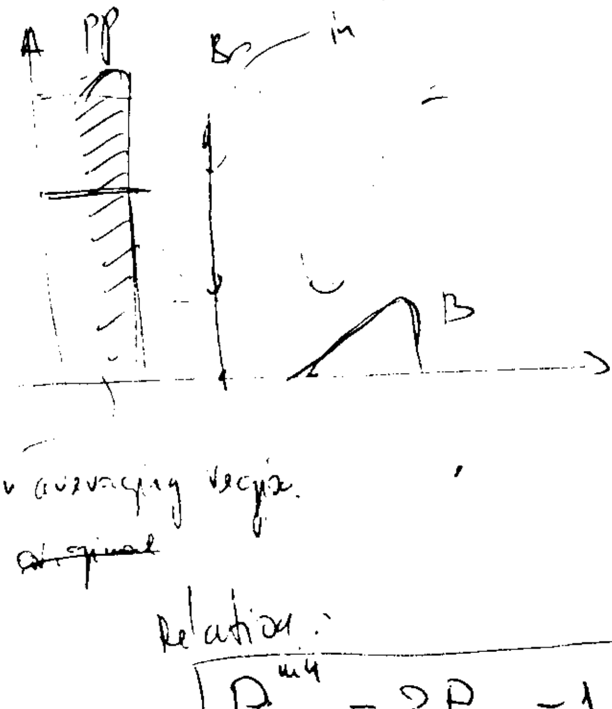
② Constant suppression (averaged oscillations.



can reproduce Kamiokande ~~Homestake~~ and Gallium results.

But not Homestake

③ Vacuum oscillations



can not give "best" fit.

Be in the rapidly oscillating region → time variations

in averaging regime.

if. ~~original~~

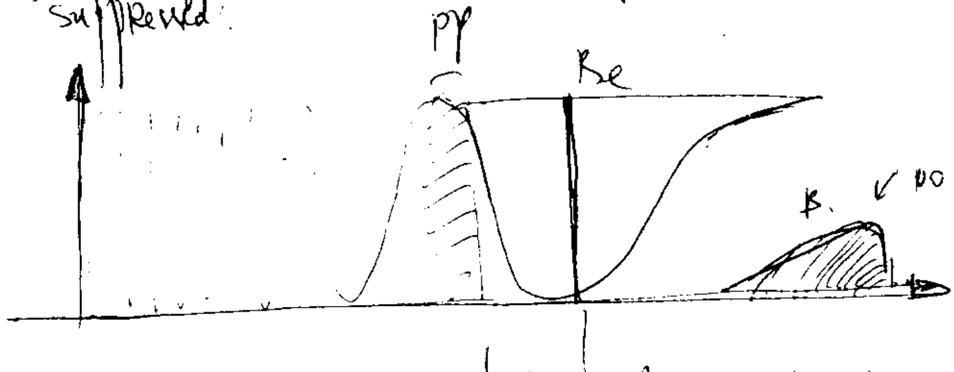
Relation:

$$\boxed{P_{Be}^{m4} = 2P_{pp} - 1}.$$

$$\boxed{\begin{array}{c}(0{,}3 - 1) \cdot 10^{-10}\ eV^2 \\ \sin^2 2\theta > 0{,}7\end{array}}$$

(0 < ... > $\frac{1}{2}$

If ~~FB~~ original boron neutrino flux is suppressed:



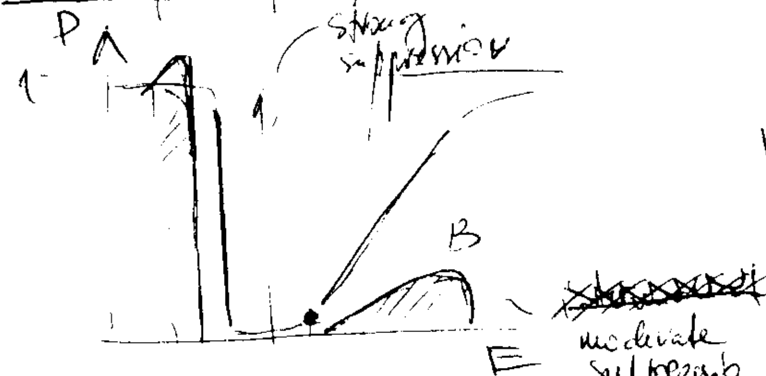
No variations. strong suppression

$\Delta m^2 = 5 \cdot 10^{-12}$ eV

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

④ Best fit of data

MSW (Resonance conversion)



$P \sim \exp\left(-\frac{E_{nc}}{E}\right)$

are not converted

depends on $\sin^2 2\theta$

non adiabatic edge ⇒ distortion of spectrum ← will be tested by SK.

$$\boxed{\begin{aligned} \Delta m^2 &= (6 \pm 2) \cdot 10^{-6}\ eV^2 \\ \sin^2 2\theta &= (10^{-3} - 10^{-2}) \end{aligned}}$$

$5 \cdot 10^{-3}$ → best fit

active
sterile

What defines Δm^2?,

1) n_e^{max} - maximal density inside the sun.

2) E_{pp}^{max}, E_{Be}

3) Gallium results

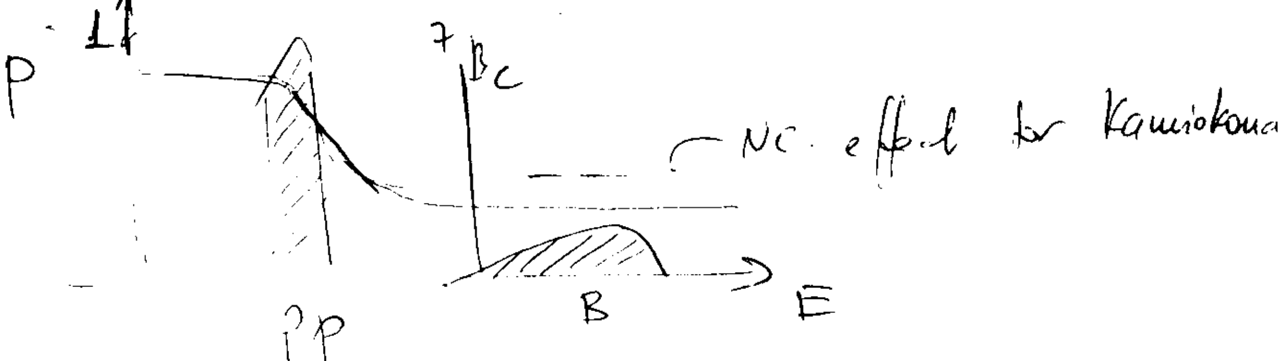
$\sin^2 2\theta$ is fixed by double ratio: R_{Ar}/R_{ve}

FB: 0.5 – 0.12

already present data allow to determine the original fluxes:

$$\boxed{F_B^{*} = (0.4 - 2.0) \cdot F_B^{SSM}}$$

"Large" mixing solution



$$\boxed{\begin{array}{l} \Delta m^2 \simeq 6 \cdot 10^{-6} - 10^{-4}\ eV^2 \\ \sin^2 2\theta = 0.3 - 0.8 \end{array}}$$

for $\frac{F_B}{F_B^{SSM}} \geq 1$

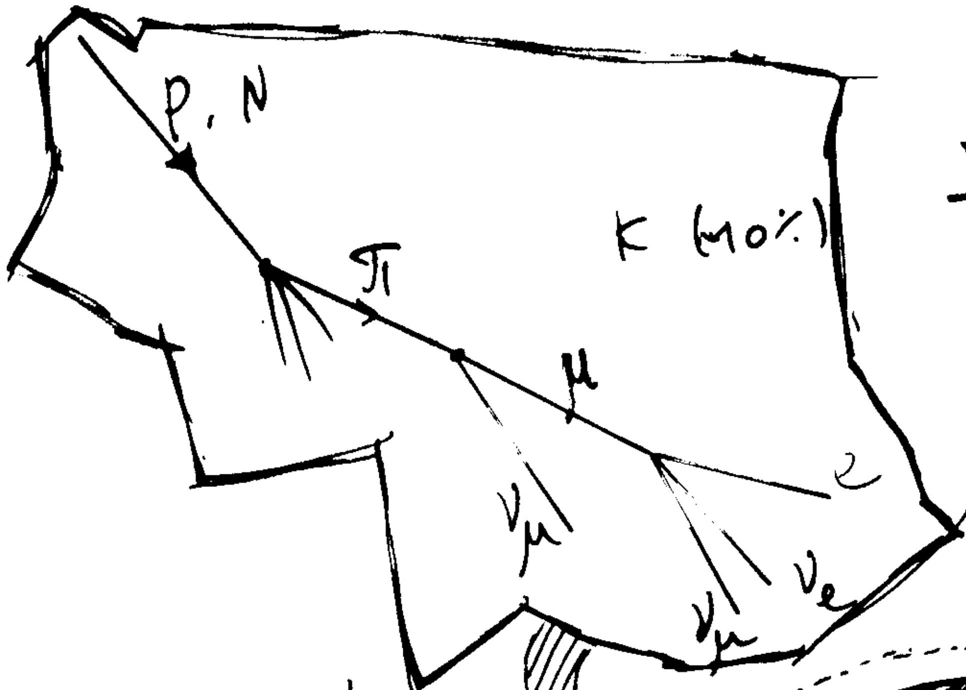
Sterile neutrinos:

$\nu_e \to \nu_s$

- $n^{eff} \neq n^e$ $\quad n_e - \frac{1}{2} n_n$
- no NC effect of ν_μ, ν_τ in Kamiokande

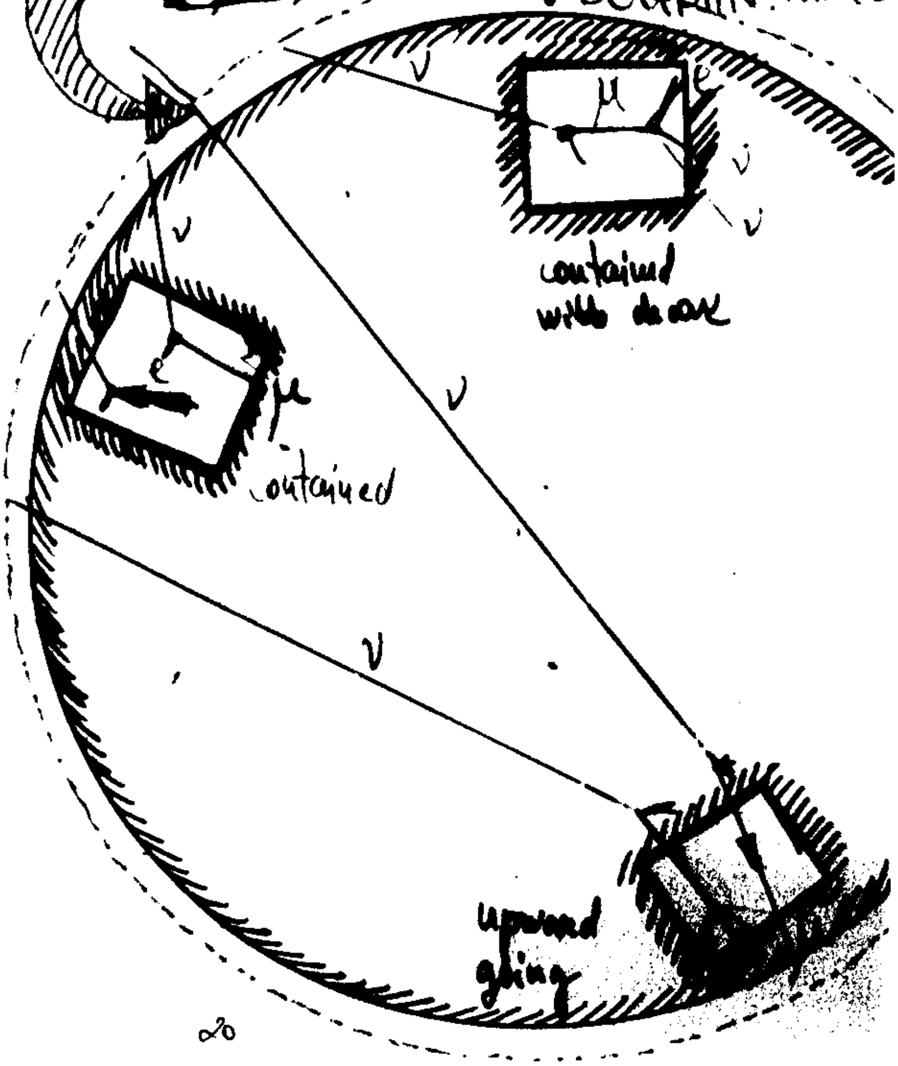
the regions of parameters are approximately the same.

Atmospheric neutrinos



$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$$

- KAMIOKANDE
- IMB
- Fréjus
- NUSEX
- BAKSAN
- ~~SCHRAN~~ MACRO



Contained events

$E_\nu \gtrsim 1 - 10$ GeV

$E_{vis} \sim 0.2 - 1.5$ GeV

- e-like (with decays)
- μ-like

(quasielastic scatt.
CC : NC → π
multi-GeV: 1-20 GeV)

- **Stopping upward g.** (Decaying μ)

  $E_\nu \simeq 20 - 100$ GeV

- **Upward going μ**

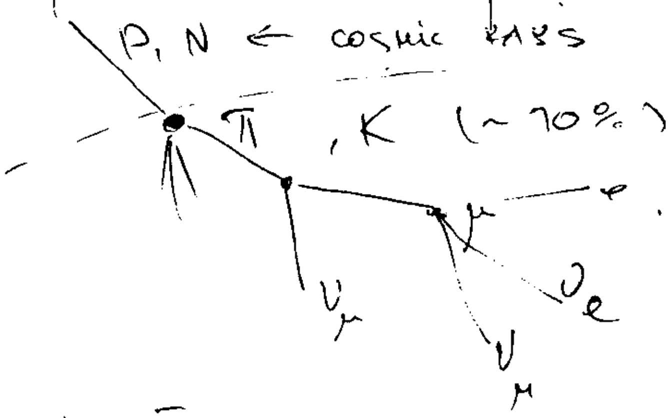
$E_\nu = 50 - 300$ GeV

E_{th} 1-2 GeV

② A'

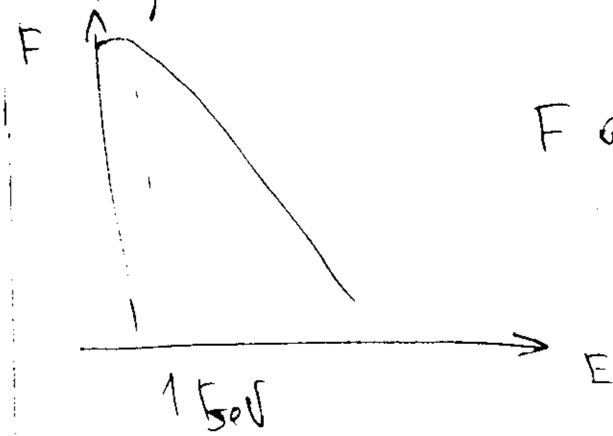
ATMOSPHERIC NEUTRINOS

produced in the atmosphere.



- $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$ roughly (absorption

- calculation of absolute values of fluxes
- normalization to observed flux of μ and e



$F \propto E^{-2.7}$

- absolute fluxes ~ 30% accuracy

ratio of ν_μ / ν_e ' ~ < 5%

- Flux (?) < absolute value ?

$p^+ \longrightarrow \pi^+$

π^+ dominate over π^- ?

2 < 1 GeV

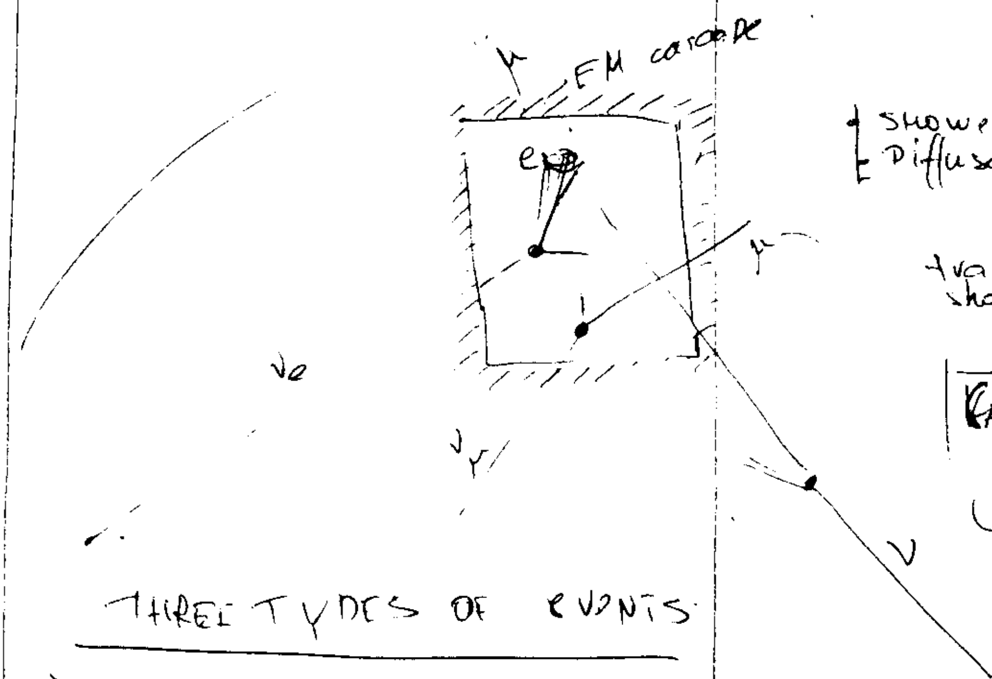
1.5

$F = 40 - 80 \frac{1}{m^2 \, s \, sr \, s}$ 1 GeV / 1 km

Detection.

UNDERGROUND installations.

+ KAMIOKANDE	+
+ IMB	+
+ Frejus	−
+ NUSEX	−
+ BAKSAN	−
+ SOUDAN	+/−
+ MACRO	? ANOMALY



Schalenform

- SHOWERS
- Diffuse RINGS

track
sharp rings

KALIBRATION:
identification
is OK.

THREE TYPES OF EVENTS

1) CONTAINED events, i.e. INTERACTION INSIDE THE INSTALLATION — QUASIelastic scattering.

$E_\nu \sim 3 - 10$ GeV

$E = 0.2 - 1.5$ GeV

2) Upward going muons. — 20 - 100 GeV

(a) stopping (decay in the detector) — 50-300 GeV.

(b) throughgoing.

$E_\nu =$

Results:

(1) DOUBLE RATIO.

$$R(\mu/e) = \frac{\left(\frac{\mu\text{-like}}{e\text{-like}}\right)_{exp}}{\left(\frac{\mu\text{-like}}{e\text{-like}}\right)_{theory\ MC?}}$$

NO energy AND ANGULAR dependence OF suppression (?)
→ AVERAGED oscillation effect.

$R(\mu/e) = 1$ (if our theory is OK)

Observation

$$\boxed{R(\mu/e) \triangleq 0.6.}$$

KAM. IMB SOUDAN.

KAMIOKANDE: $0.60^{+0.06}_{-0.05}$

SOUDAN: $0.64 \pm 0{,}17 \pm 0.09$

Deficit of ν_μ ($\bar{\nu}_\mu$) ?
or excess of ν_e ($\bar{\nu}_e$).

- no effect in Frejus, NUSEX, MACRO? ; H.E.
- NO effect in MEASUREMENTS OF UPWARD GOING MUONS.

ANOMALY AT LOW ENERGIES ?

INTERPRETATION:

in this region one can reconcile all the DATA.

Oscillations: $\nu_\mu \to \nu_\tau$

$\Delta m^2 \sim (0.4 - 3) \cdot 10^{-2}\ eV^2$
$\sin^2 2\theta = 0.5 - 0.6$

- proton decay $p \to e^+ \nu\nu$ (excess of e)

← matter effect.

$M_{Atm} = 0.1\ eV$

$\nu_\mu \to \nu_e$
$\Delta m^2 = (0.5 - 2) \cdot 10^{-2}\ eV^2$
$\sin^2 2\theta \simeq 0.4 - 0.6$

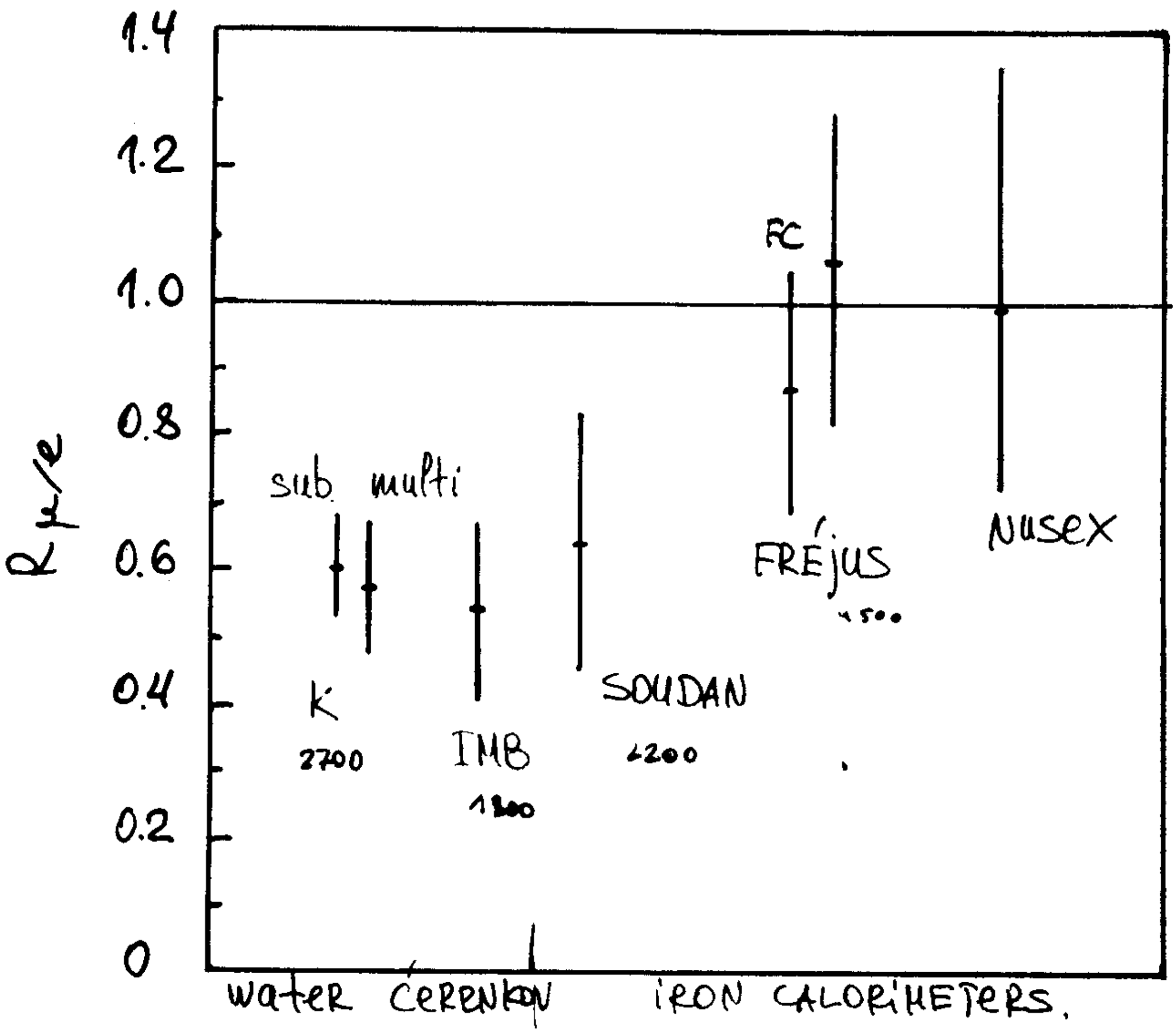
(like, what recent H.E!)

LONG BASELINE EXPERIMENTS

Atmospheric Neutrino Problem

DOUBLE RATIO: $$\boxed{R_{\mu/e} \equiv \frac{(\mu\text{-like})/(e\text{-like})_{data}}{(\mu\text{-like})/(e\text{-like})_{MC}}}$$

<5% uncertainty



KAM. I+II+III	$0.60^{+0.06}_{-0.05} \pm 0.05$	sub GeV
	$0.57^{+0.08}_{-0.07} \pm 0.07$	multi GeV
IMB-3	$0.54 \pm 0.05 \pm 0.12$	
SOUDAN-II	$0.64 \pm 0.17 \pm 0.09$	

$\uparrow$
$R_{\mu e}$

Calibration
identified ...

90% C.L. allowed neutrino-oscillation parameters

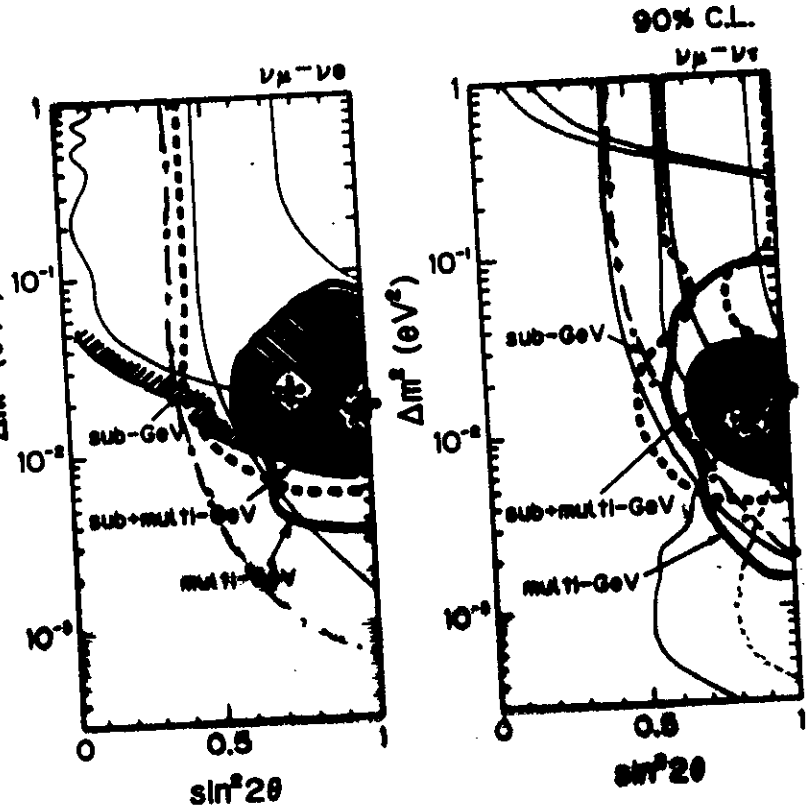


Fig.5

Lipari
Lusignoli
Sartogo

excluded: KRASNOYARSK
BUGEY -3
-4

Fuejus

KAMIOKANDE : multi GeV energy range
= ANGULAR DEPENDENCE ?
OF THE EFFECT

$E_{vis} > 1.3$ GeV

$\overline{E}_\nu \sim 7$ GeV

e-like 98 events (FC)

μ-like 135 events = 31 (FC) + 104 (PC)

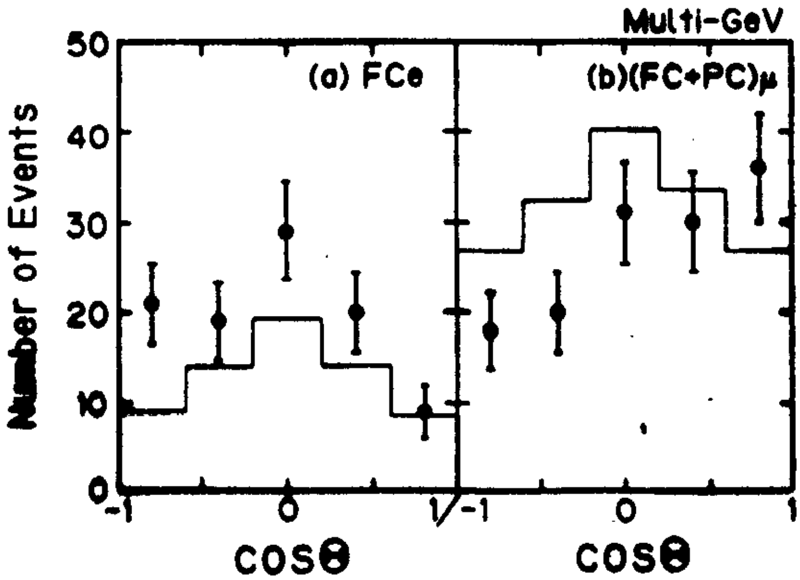


Fig.3

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Atmospheric neutrino problem AND LONG BASELINE EXP.

(as essence of)

KAMIOKANDE :

- KEK exp. identification.
- multi-GeV DATA:

-ANGULAR DEPENDENCE

-ENERGY DEPENDENCE

OSCILLATIONS.

MAXIMAL MIXING ?

IMB limit exclusion from stopping/passing muons is relaxed

Lipari, Lusignoli SARTOGO

FREJUS :

New ANALYSIS OF DATA ⇒ excludes MOST PART of the ALLOWED REGION.

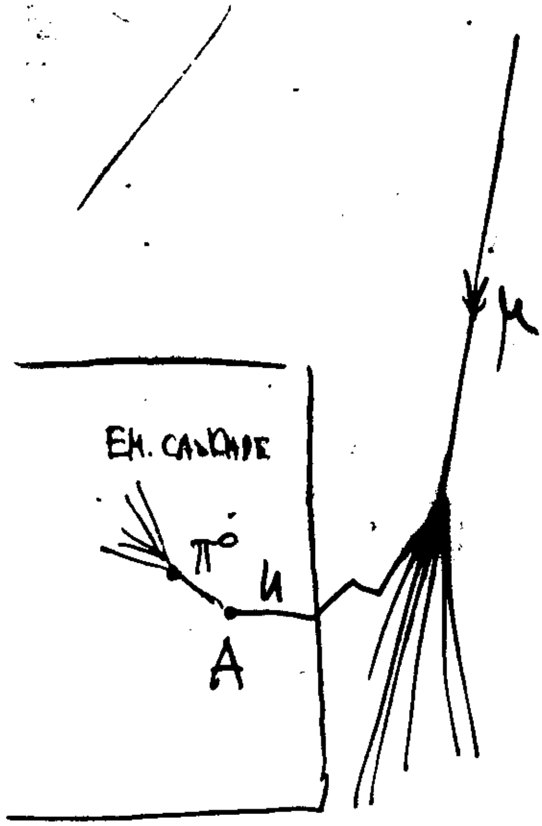
BUGEY 3-4 + KRASNOYARSK:

excludes MOST PART of $\Delta m^2 - \theta$ region OF $\nu_e - \nu_\mu$ - OSCILLATIONS

NEUTRON Background

O. Ryazhskaya.

Excess of e-like events due to neutrons?



O. Ryazhskaya
Nov. 94

$n + A \to \pi^0 X$

can immitate e-like event

$E \approx 0.2 - 5$ GeV

Table 2

	DETECTOR					
	IMB		Kamiokande (E<1,33 GeV)		Kamiokande (E>1,33 GeV)	
	experim.	backgr.	experim.	backgr.	experim.	backgr.
Single ring events:						
Total	610	~250	389	~54	195	
showering (e-like)	378	210	191	46	98	~40
nonshowering (μ-like)	232	<40	198	<8	31	
(μ/e) data:						
without taking into account the background	0,61		1,04		0,32	
taking into account the background	~1,1		~1,4		0,53	
(μ/e)MC [1-3]	1,1		1,6		0,57	

30% – 40% indication

• Kam: ≤ 1% (2)

• IMB – MC-~~simulation~~

• μ-deficit rather ~~than~~ e-excess?

$\boxed{\text{LSND}}$

Čerenkov

$\pi^+ \to \mu^+ + \nu_\mu$ 30 m

$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$

$\bar{\nu}_\mu \to \bar{\nu}_e$?

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

$n \rightsquigarrow 2\gamma$

E 36 – 60 MeV

- 9 events
- background from conventional sources

2.1 ± 0.3 ev

$$P = \left[0.34 \,{}^{+0.20}_{-0.18} \pm 0.07\right] \%$$

$$\boxed{\Delta m^2 = \frac{6 \cdot 10^{-2}\ \text{eV}^2}{\left[\sin^2 2\theta\right]^{1/2}}}$$

$\sin^2 2\theta \sim 1.5 \cdot 10^{-3} - 4 \cdot 10^{-2}$

$\Delta m^2 < 3.$

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KARMEN

IMPLICATIONS

① solar neutrino mass scale :

$$m_{\odot} \approx \sqrt{\Delta m^2} \approx \boxed{2.5 \cdot 10^{-3} eV}$$

(which as we will see can be reproduced quite well by the see-saw mechanism)

② The desired angle can be discribed quite well by formula

$$\theta_{e\mu} \simeq \sqrt{\frac{m_e}{m_\mu}} - e^{i\Phi}\,\theta_\nu .$$

(or some modification of these).

→ similar to what one has in q-sector.

"STANDARD" SCENARIO OF NEUTRINO MASSES AND MIXING.

1. Neutrino masses are generated by the See-Saw mechanism with Majorana masses of the RH components:

$$\boxed{M_R \simeq 10^{12}\ \text{GeV}}$$

<u>Remarks on the See-Saw.</u>

In the first lecture we introduced general form of the mass matrix

if ν have RH components: $= \nu_R \Rightarrow \nu_L^c$.

then for 1 generation one gets:

$$\begin{array}{c|cc|} \nu_L & m_L & m^D \\ \nu_L^c & m^D & M_R \end{array}$$

suppose first $\boxed{m_L = 0}$ (or very small.)

THE IDEA:

① Dirac masses of neutrinos are of the SAME ORDER as Dirac MASSES of charged fermions from the same generation.

$$m_\nu^D \sim m_l^D \, , m_u^D$$

(NATURAL)
q - l
symmetry

② RH neutrinos have majorana masses:

$$M_R.$$

since majorana mass term is singlet of SM group

→ the mass M_R is not protected by the SM symmetry:
can be

$$M_R >>> m_W$$

③ for $m^D << M_R$ the Diagonalization gives for lightest component.

$$\boxed{m \simeq - \frac{m_D^2}{M_R}} << m_D$$

<u>THUS:</u> see-saw gives <u>NATURAL</u> explanation of smallness of <u>NEUTRINO masses</u>.

Smallness of m_ν is related to neutralness of neutrinos

ν: neutral

may have majorana mass terms

RH component are singlets

the mass can be very large

light component is very light

For three generations

$$\begin{vmatrix} 0 & \hat{m}^D \\ \hat{m}^D & \hat{M}_R \end{vmatrix}$$

$$\boxed{m = -m^D M_R^{-1} m^{D\,T}}$$

3×3 matrices

$m_L = ?$ SO_{10}, L-R symmetric models:

M_R is generated by triplet of Higgses Δ_R (126)

Δ_L Δ_R

then triplet exists which aquire the induced mass

m_L can be zero
in virtue of
absence of corresponding
~~mu~~ higgs multiplets or
due to smallness of some
coupling constant.

(2). If $\nu_\odot$-problem is solved by
$\nu_e \to \nu_\mu$ resonance conversion one gets:
according ~~...~~ to the see-saw.

$$M_R = \frac{m_D^2}{m_\odot} \simeq 4 \cdot 10^{11}\ \text{GeV}$$

if $M_D \sim 1$ GeV (typical mass of second generation)

$\frac{1\ \text{GeV}}{10^{+9}}$ / $\cdot 10^{-3}$

10^{-12}

GeV

(3) If all M_R (for all generation have similar) values!
then for $(\nu_\tau \approx \nu_3)$ one gets:

$$m_3 \simeq \frac{M_{3D}^2}{M_R} > \underline{\underline{6\ \text{eV}}}$$

in the cosmologically interesting domain

for $M_{3D} \approx 50$ GeV

ν_3 5 - 7 eV HDM

ν_2 $\sim 2.5 \cdot 10^{-3}$ eV $\qquad m_1 \sim$

$\nu_\odot$ ...

$2 \cdot 10^{-8}$ eV ν_1

(4) $M_R = 10^{11} - 10^{12}$ GeV

→ intermediate scale

. origine ?

- SUSY breaking scale (?)

  if ν_R^c are communicated to hidden sector?

- PQ (Peccei-Quinn) scale

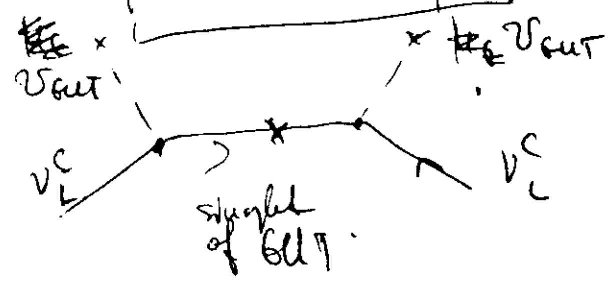
  = $U(1)_L \equiv U_{PQ}(1)$.

  $\nu^{c\,T} \nu^c \sigma$

- effective scale originates from M_{GU} and M_{pl} ?

$$\boxed{M_R \sim \frac{M_{GU}^2}{M_{pl}}}$$

10^{16}



$$\frac{16\ 16 \cdot 16\ 16}{M_{pl}}.$$

(5) Mixing: depends on structure of M_R

M_R can enhance mixing.

- If M_R is close to $\hat{I}$, then the mixing is determined essentially by M_D and thus similar to quark mixing

CP-phase

∴ →

- However special structure of M_R may result in strong enhancement of lepton mixing in comparison with quark mixing

Simple example:

$$M_R \cong M_0 \begin{vmatrix} 0 & 1 \\ 1 & 0 \end{vmatrix}$$

$$m_D = \begin{vmatrix} m_1 & 0 \\ 0 & m_2 \end{vmatrix}$$

$$m \sim \frac{1}{M_0} \begin{vmatrix} 0 & m_1 m_2 \\ m_1 m_2 & 0 \end{vmatrix}$$ → off diagonal

small correction:

$$M_R = M_0 \begin{vmatrix} \epsilon & 1 \\ 1 & \epsilon' \end{vmatrix} \qquad \epsilon, \epsilon' \ll 1$$

lead to pseudo-Dirac structure.

The structure of M_R is $\approx$ fixed if ν_R enter the same multiplet as ν_L (SO_{10})

$\Rightarrow$ one expect some relation between quark and lepton mixing.

$\nu_e - \nu_\tau$ mixing

$$\underline{\theta_{e\tau} \sim k\, V_{ub}} \qquad k = \frac{1}{3} \div 3.$$

$\sin^2 2\theta_{e\tau} \approx 10^{-5}$

3·10^{-3}
1·10^{-5}

is just the bound from the nucleosynthesis of heavy elements (r- processes) in the inner part of SN.

$$\boxed{\sin^2 2\theta_{e\tau} \lesssim 5 \cdot 10^{-5}}$$

- $\nu_\tau \to \nu_e$ conversion in SN

- $E(\nu_e) > E(\bar{\nu}_e)$

then $p + \bar{\nu}_e \to e^+ + n$.

$n + \nu_e \to e^- + p$

will dominate:
p-reach medium $\to$ no production of heavy element ($Z > 26$)

Qian
Fuller

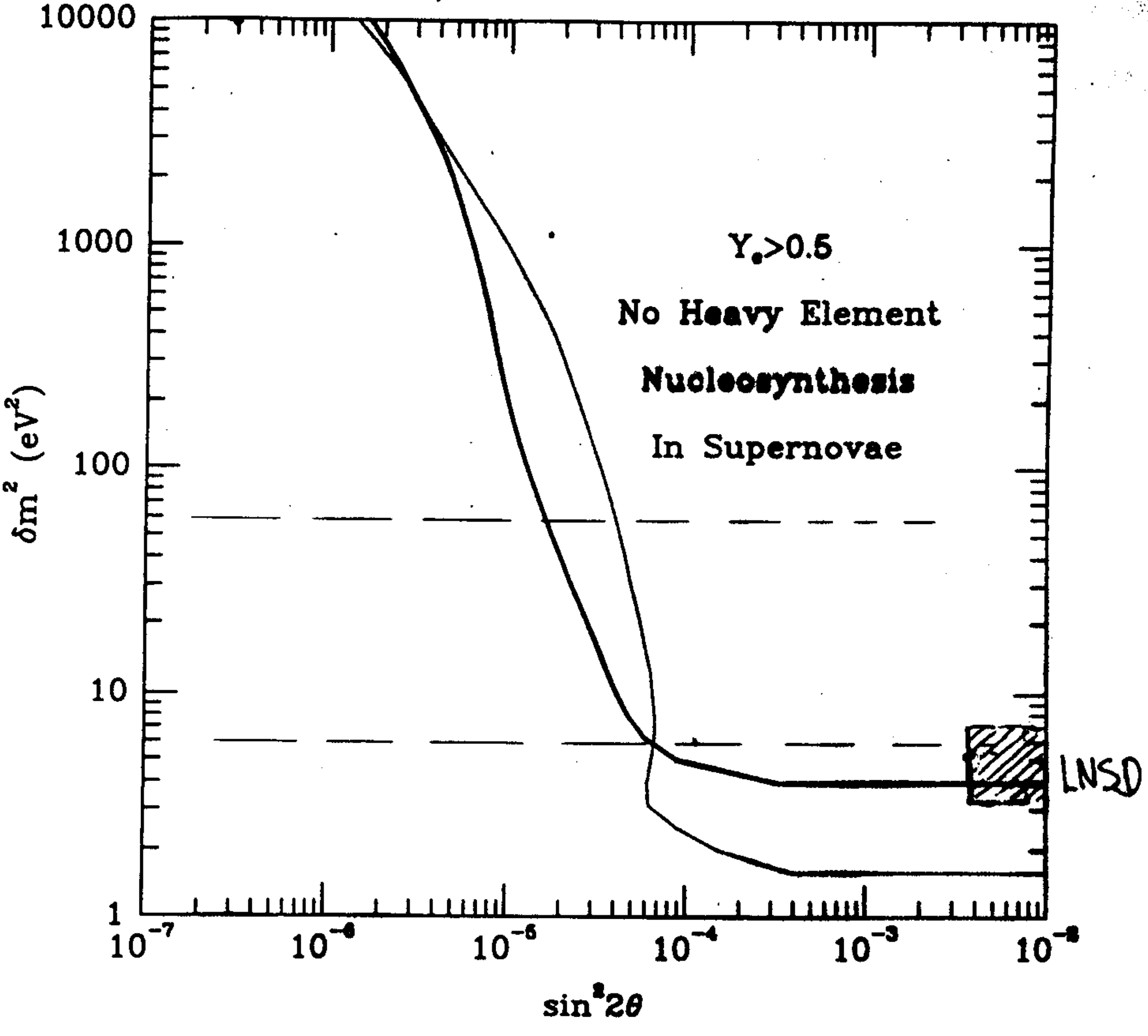


Fig. 9

$\boxed{\nu_\mu - \nu_\tau}$ mixing

$$\boxed{\theta_{\mu\tau} \sim k V_{cb} \eta}$$

$k = \frac{1}{3} - 3$

η is the renormalization factor

If $m_3 = 5$ eV

$\boxed{\begin{matrix}\text{CHORUS} \\ \text{NOMAD}\end{matrix}}$ } will cover all this region

for $m_3 < 2$ eV $\Rightarrow$ No

operate now

• $\boxed{\text{E 803}}$ can cover ....

LSND / KARMEN

$\bar{\nu}_\mu - \bar{\nu}_e$ oscillations ~~explain~~ for

• the depth the oscillations

• Minakata

• Babu PATI Wilzcheck

$$\boxed{A = 4 |U_{3\mu}|^2 |U_{3e}|^2}$$

E531 CHARM

bound from BUGEY

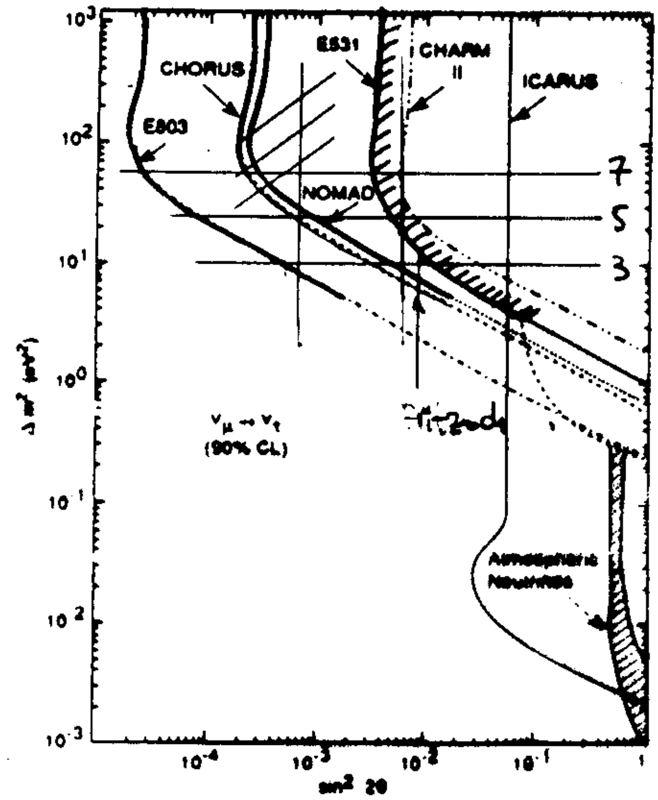
$J_0 \lesssim 10^{-3}$,

LSND: $3.4 \quad 10^{-3}$

Table 3

Summary of background, efficiency and sensitivity for NOMAD, CHORUS, E803

	NOMAD	CHORUS	E803
Number of CC interactions	1.1×10^6	5×10^5	6×10^6
Expected running time (yrs)	≥ 2	2	4
τ decay mode	e, μ $\pi^- + (n\pi^0)$ $\pi^+\pi^-\pi^- + (n\pi^0)$	μ $\pi^- + (n\pi^0)$ $\pi^+\pi^-\pi^- + (n\pi^0)$	e $\pi^- + (n\pi^0)$ –
Total efficiency = Σ(EFF*BR)	0.048	0.096	0.21
Expected number of events at the E531 limit: Large Δm^2, $\sin^2 2\theta = 5 \times 10^{-3}$	78	64	600
Expected number of background events	6.8	0.4	1.2
Sensitivity at large Δm^2			
$\sin^2 2\theta_{\mu\tau} <$	3.8×10^{-4}	2.8×10^{-4}	2.8×10^{-5}
$\sin^2 2\theta_{e\tau} <$	2.7×10^{-2}	1.6×10^{-2}	1.4×10^{-3}
Start-up date	1994/5	1994	1998



DM

14_ν, eV

Figure 10: The regions expected to be excluded, at the 90% CL, in the Δm^2–$\sin^2 2\theta$ plot by CHORUS, NOMAD and E803 if no ν_μ–ν_τ oscillations are observed.

| | cheng
Gell
Hall

From L. Camilleri
CERN

H. Fritzsch $\sin^2 2\theta \sim 8.5 \cdot 10^{-3}$

Other consequences.

- Lepton ~~[illegible]~~ asymmetry in the Universe:
in the decays
$$N \to e^+ \Phi$$
$$\quad\;\; e^- \Phi^+$$
(?)

$\Rightarrow$ converted into baryon asymmetry..

- Renormalization effects due to Dirac interactions of neutrinos
from M_R to M_{GU}.

= b – τ – unification
= large tan β

Scenario with
4 sterile neutrino

ν_e 3 MDM

$\nu_{ATM.}$

S LSND $\longrightarrow$ problem with r-processes

$\nu_\odot$

(1) $m_s \sim 2.5 \cdot 10^{-3}$ eV
S mixes essentially with ν_e

(2) ν_μ - ν_τ form pseudodirac neutrino
$\approx$ maximal mixing

~~Origin of S~~ (?)
such a picture: if there is some horizontal symmetry.

ν_e ν_μ ν_τ
0 1 -1

S 0 singlet

couple with R.H neutrinos only