NNN'02

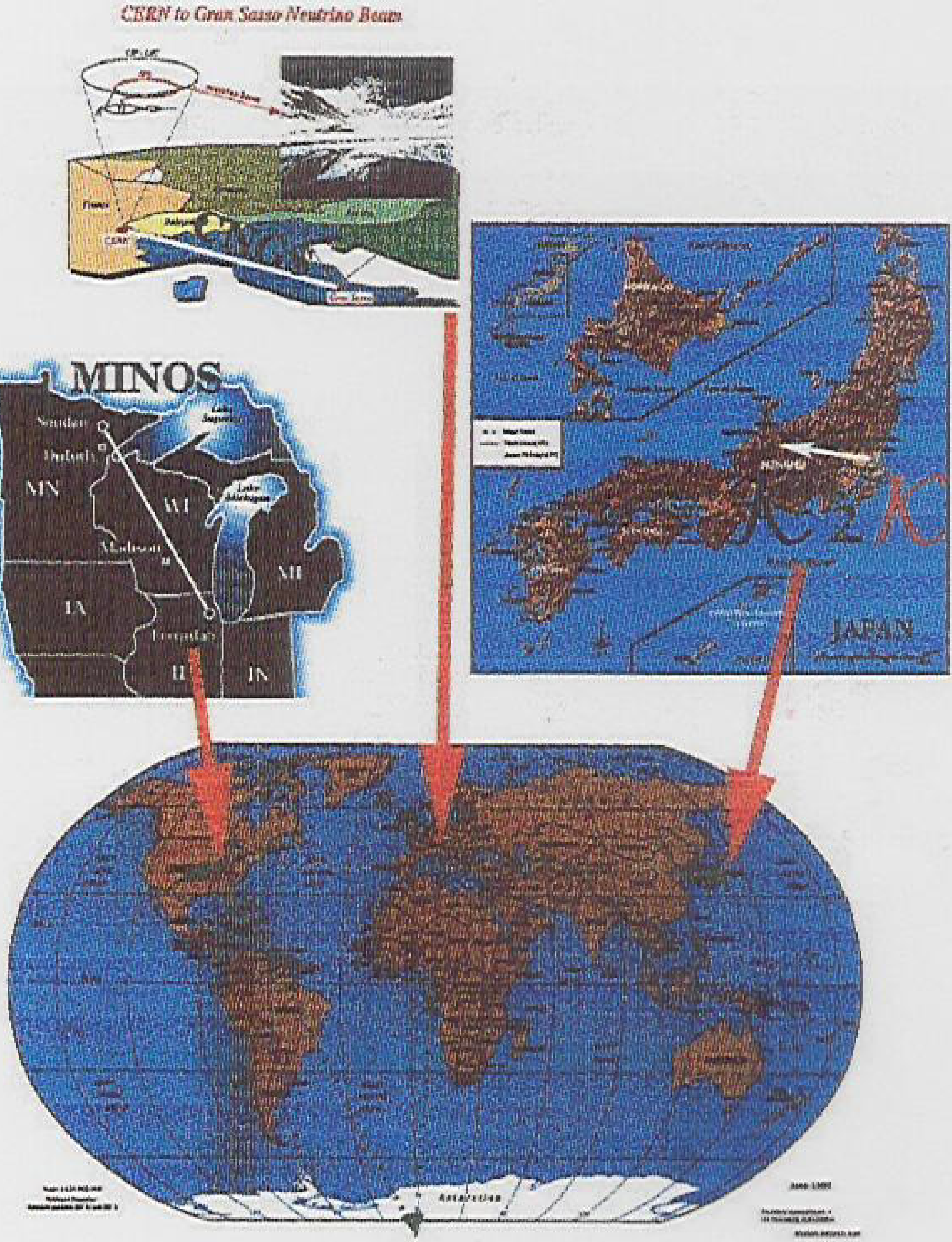
PHENOMENOLOGY of ν'OSCILLATIONS

- Consisting Evidence for ν' Masses & Mixings from Atmospheric & Solar.
- Established Facts if LBL, Reactor confirm.
- U_{e3} ? , $\cancel{CP}$?
- Sign [Δm^2] , Absolute Mass
- Dirac or Majorana ?

J.B.
U. Valencia.

Neutrinos as a Unique Probe: $10^{-33} - 10^{+28}$ cm

- Particle Physics
  - $\nu N, \mu N, e N$ scattering: existence/ properties of quarks, QCD
  - Weak decays ($n \to p e^- \bar{\nu}_e, \mu^- \to e^- \nu_\mu \bar{\nu}_e$): Fermi theory, parity violation, mixing
  - Neutral current, Z-pole, atomic parity: electroweak unification, field theory, m_t; severe constraint on physics to TeV scale
  - Neutrino mass: constraint on TeV physics, grand unification, superstrings
- Astrophysics/Cosmology
  - Core of Sun
  - Supernova dynamics
  - Atmospheric neutrinos (cosmic rays)
  - AGNs, cosmic rays, violent events, GRB
  - Large scale structure (dark matter)
  - Nucleosynthesis (big bang - small A; stellar - to iron; supernova - large N)
  - Baryogenesis
  - Simultaneous probes of ν and astrophysics


CERN to Gran Sasso Neutrino Beam
MINOS
Soudan
Duluth
MN
WI
MI
Madison
IA
Fermilab
IL
IN
JAPAN
Antarctica

- NEUTRINO OSCILLATIONS

For 3 families of <u>active</u> massive ν's, with mixing,

$$\nu_\alpha = \sum_i U_{\alpha i}\, \nu_i + \underbrace{\cdots}_{\text{sterile}}$$

[ν_i are either D or M] ← later

- Flavour Evolution in Vacuum

$$|\nu_\alpha(t)\rangle = \sum_\beta |\nu_\beta\rangle \left(\sum_i U_{\beta i}\, e^{-iE_i t}\, U^*_{\alpha i} \right) + \underbrace{\cdots}_{\text{sterile}}$$

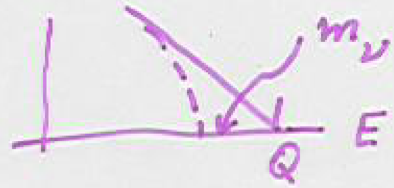
- Transition Probability

$$\boxed{P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} + 2\,\mathrm{Re} \sum_{j<k} U_{\beta j} U^*_{\alpha j} U^*_{\beta k} U_{\alpha k} \left(e^{-i \Delta m^2_{jk} \frac{L}{p}} - 1 \right)}$$

- $\Delta m^2_{jk} \frac{L}{p} \ll 1,\ \forall (j,k) \Rightarrow P(\nu_\alpha \to \nu_\beta) \to \delta_{\alpha\beta}$

- DIRECT MEASUREMENT OF ν-MASS

Reminder : If $m_\nu \neq 0$, the hard part of β-spectra will be distorted $\longrightarrow$ plot



The "classical" decay is

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

[superallowed transition, simple atom, small energy release $Q = 18.6$ keV, ...]

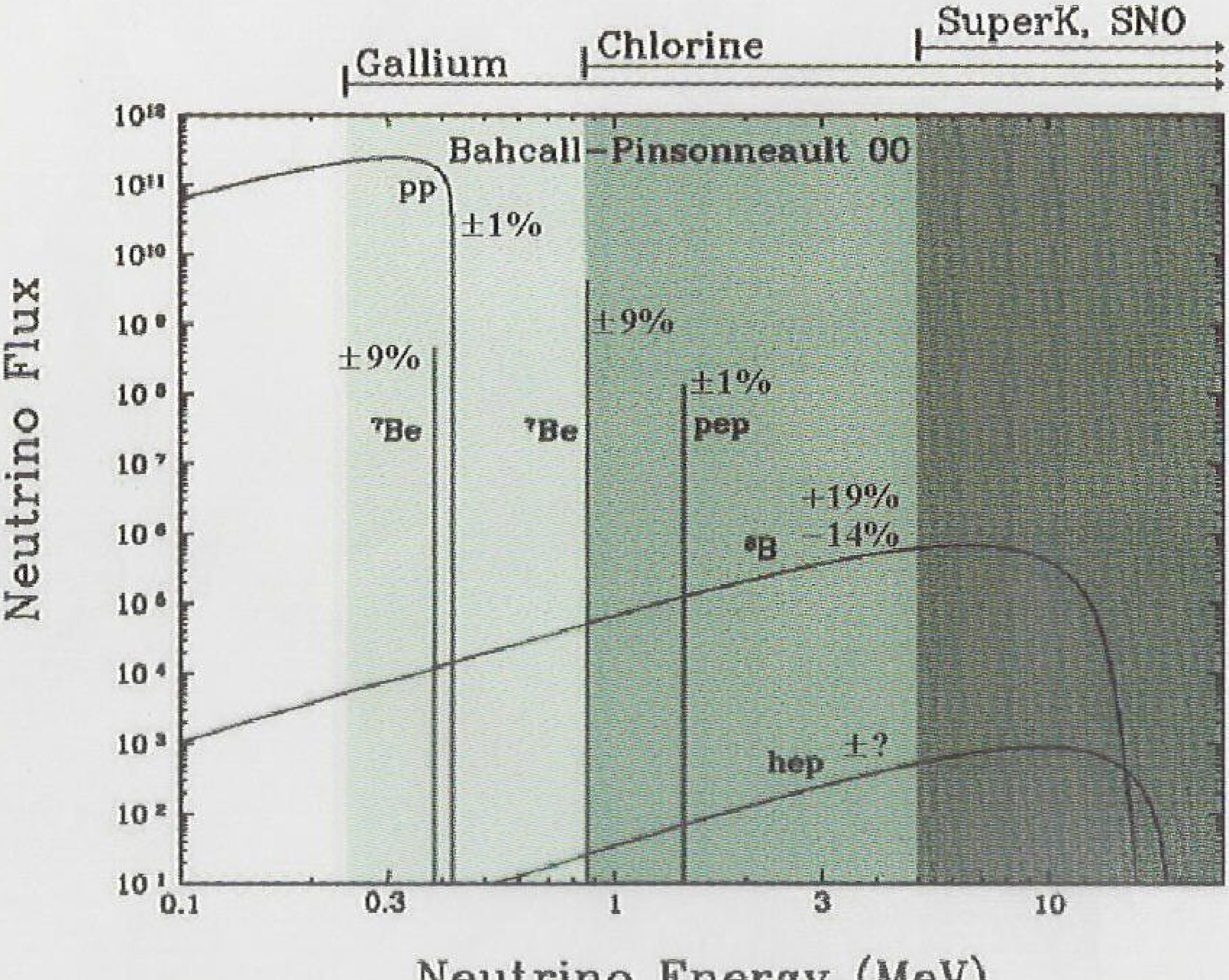
The spectrum is determined by phase space

$$\frac{dN}{dT} = C\, p\, E\, (Q-T)\sqrt{(Q-T)^2 - m_\nu^2}\;\; F(E)$$

Fermi function

m_ν is mass of ν_1
["kinks" at lower E's for $\nu_{2,3}$]

Experimental spectrum is fitted by m_ν^2 and many other parameters (Q, background term, normalization, ---) $\Rightarrow$ From Present Day Experiments, NO INDICATION IN FAVOUR OF $m_\nu \neq 0$



SuperK, SNO
Chlorine
Gallium
Bahcall-Pinsonneault 00
pp
±1%
±9%
±9%
±1%
^{7}Be
^{7}Be
pep
+19%
-14%
^{8}B
hep
±?
Neutrino Flux
Neutrino Energy (MeV)
0.1
0.3
1
3
10

- To observe ν-oscillations,

  1) At least one Δm^2

  $$\Delta m^2 \gtrsim \frac{p}{L}$$

  2) Mixing of Prepared and Detected Flavours to common Mass-eigenstates

- Types of Experiments:

  1) Appearence Experiments

  $$\underset{\nu_\alpha}{\text{CC}} \xrightarrow{\quad L \quad} \underset{\nu_\beta \neq \nu_\alpha}{\text{CC}}$$

  Ej.: $\bar{\nu}_\mu$-beam $\rightarrow$ $\bar{\nu}_e + p \to e^+ n$

  2) Disappearence Experiments

  $$\underset{\nu_\alpha}{\text{CC}} \xrightarrow{\quad L \quad} \underset{\nu_\alpha}{\text{CC}}$$

  Ej.: Solar ν_e

  $\nu_e d \to e^- p p$

  $\Rightarrow$ Survival Probability

  3) Combination of 1) + 2)

  $$\underset{\nu_\alpha}{\text{CC}} \xrightarrow{\quad L \quad} \underset{\nu_\beta}{\text{CC} + \text{NC}}$$

  E-dependent

  Ej.: Solar ν_e

  $\nu_x + e^- \to e^- \nu_x$

- SYMMETRIES

$\nu \to \bar{\nu} \implies U \to U^*$

$CPT \rightsquigarrow A(\bar{\alpha} \to \bar{\beta}; t) = A^*(\alpha \to \beta; -t)$

$T \rightsquigarrow |A(\beta \to \alpha; t)| = |A(\alpha \to \beta; t)|$

$|A(\bar{\beta} \to \bar{\alpha}; t)| = |A(\bar{\alpha} \to \bar{\beta}; t)|$

$CP \rightsquigarrow |A(\bar{\alpha} \to \bar{\beta}; t)| = |A(\alpha \to \beta); t)|$

i) $\cancel{CP}$, $\cancel{T}$ in Appearance only

$A^*(\alpha \to \alpha; -t) = A(\alpha \to \alpha; t)$

In $\alpha \to \alpha$, CPT $\Rightarrow$ CP Equality

ii) CP-odd Probability

$D_{\alpha\beta} \equiv |A(\alpha \to \beta; t)|^2 - |A(\bar{\alpha} \to \bar{\beta}; t)|^2$

UNIQUE for 3 Flavours

$$\boxed{D_{e\mu} = D_{\mu\tau} = D_{\tau e}}$$

iii) T-odd Probability

$T_{\alpha\beta} \equiv |A(\alpha \to \beta; t)|^2 - |A(\beta \to \alpha; t)|^2$

$\xrightarrow{CPT} |A(\alpha \to \beta; -t)|^2$

is ODD function of t (L).

The Pontecorvo MNS Matrix

$$\begin{Bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{Bmatrix} = U \begin{Bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{Bmatrix} \Leftrightarrow$$

For Flavour oscillations

U : 3 mixings, 1 phase

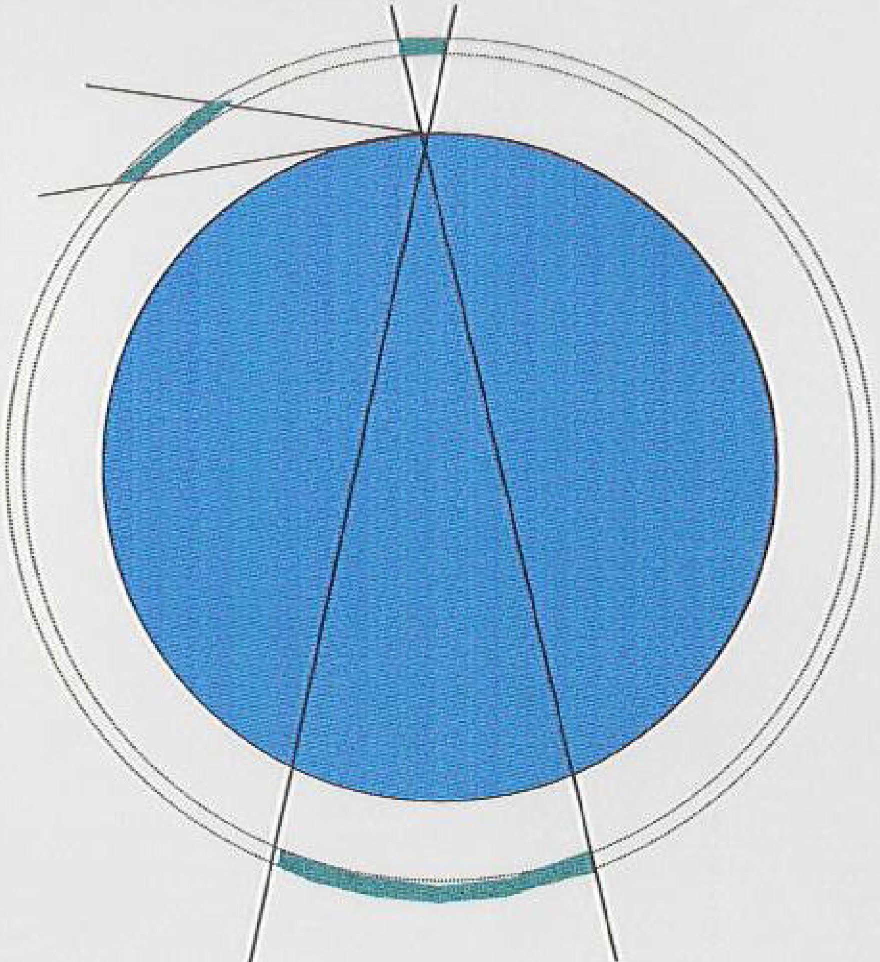
$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\simeq \text{ Atmospheric, LBL-beams}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\simeq \text{ Solar, Reactor (if LMA-MSW)}}$$

? ?

Atmospheric (through Matter)?

Reactor ?

Appearance $\nu_\mu \to \nu_e$!



Up-Down Simmetry **does not imply** isotropy:

$V_{\nu\ source}(\theta+\delta\theta) \propto l^2(\theta)/\cos\theta_{emission}$

need for 2 necessary ingredients:

1) 3D calc with the whole spherical geometry of earth

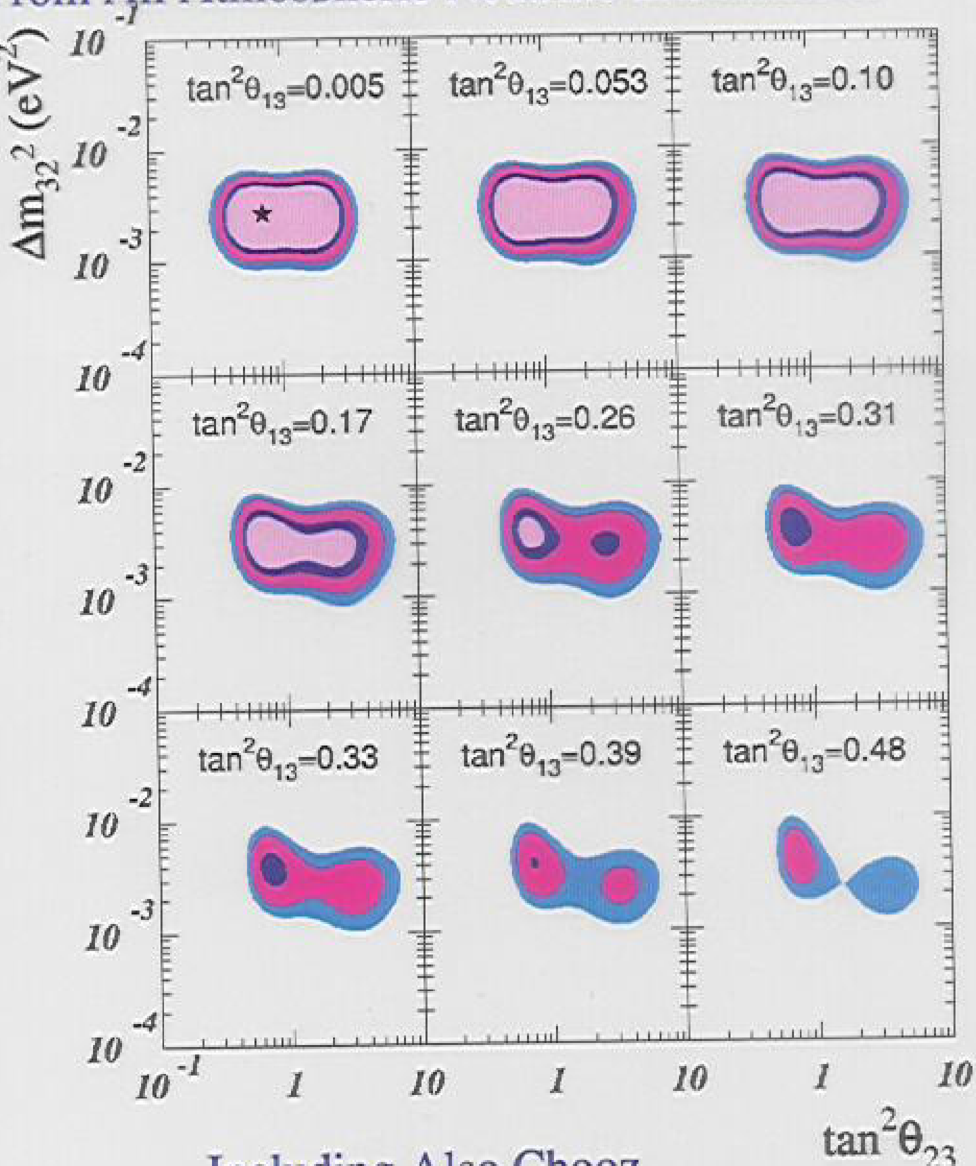
2) consider the $\langle\theta_{emission}{}^2\rangle \neq 0$ [after particle production, decay and transport]

➡ Enhancement of flux on the horizontal direction

3–ν Atmospheric Neutrino Oscillation Parameters

Update of M.C.G-G, M. Maltoni, C. Peña-Garay, J. Valle, PRD63 (2001)

From All Atmospheric Neutrino Experiments



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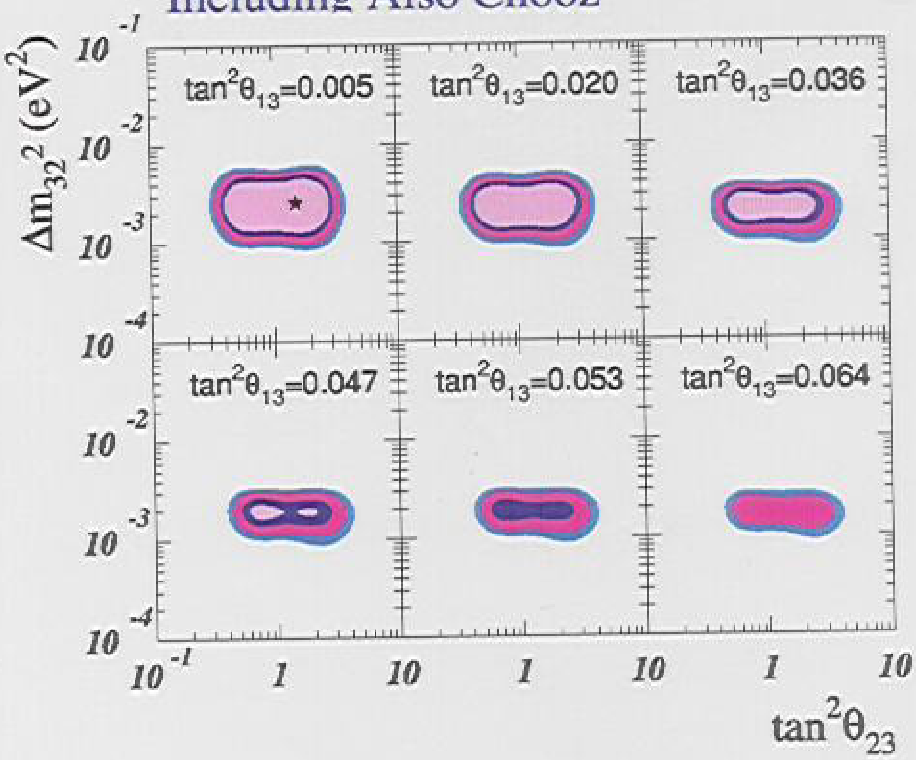
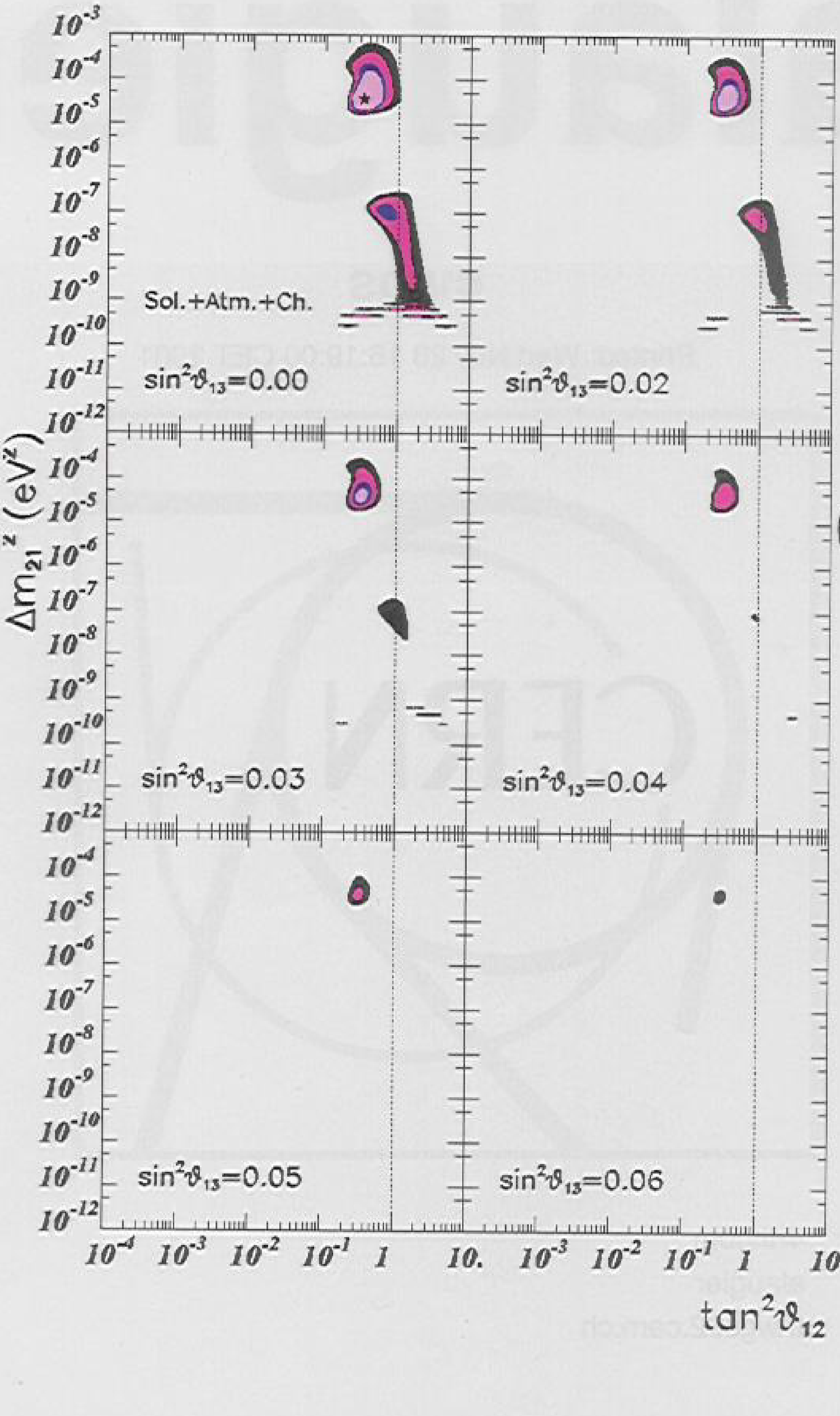
Including Also Chooz



3–ν Combined Analysis

Effect of Reactor + Atmospheric Data in Solar Regions



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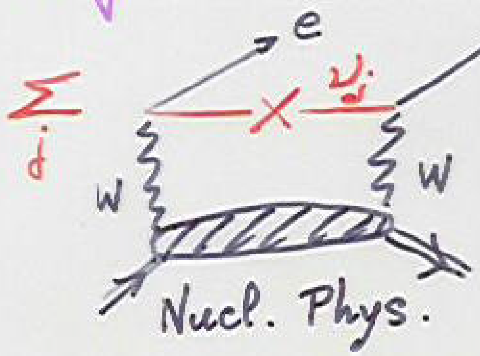
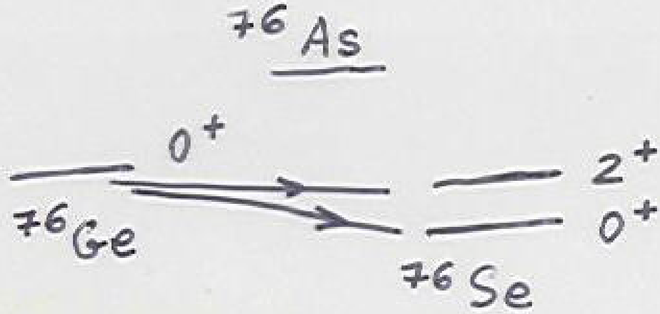
The best way to test Dirac or Majorana is to search for $\beta\beta_{0\nu}$:

$$(A, Z) \to (A, Z+2) + e^- + e^-,$$

allowed if L is not conserved.

Majorana mass term $\Rightarrow \Delta L = 2$.





The propagator is here

$$\nu_{eL}(x_1)\, \nu_{eL}^T(x_2) =$$

$$= -\sum_i U_{ei}^2 \frac{1-\gamma_5}{2} \chi_i(x_1)\, \bar{\chi}_i(x_2) \frac{1-\gamma_5}{2} C$$

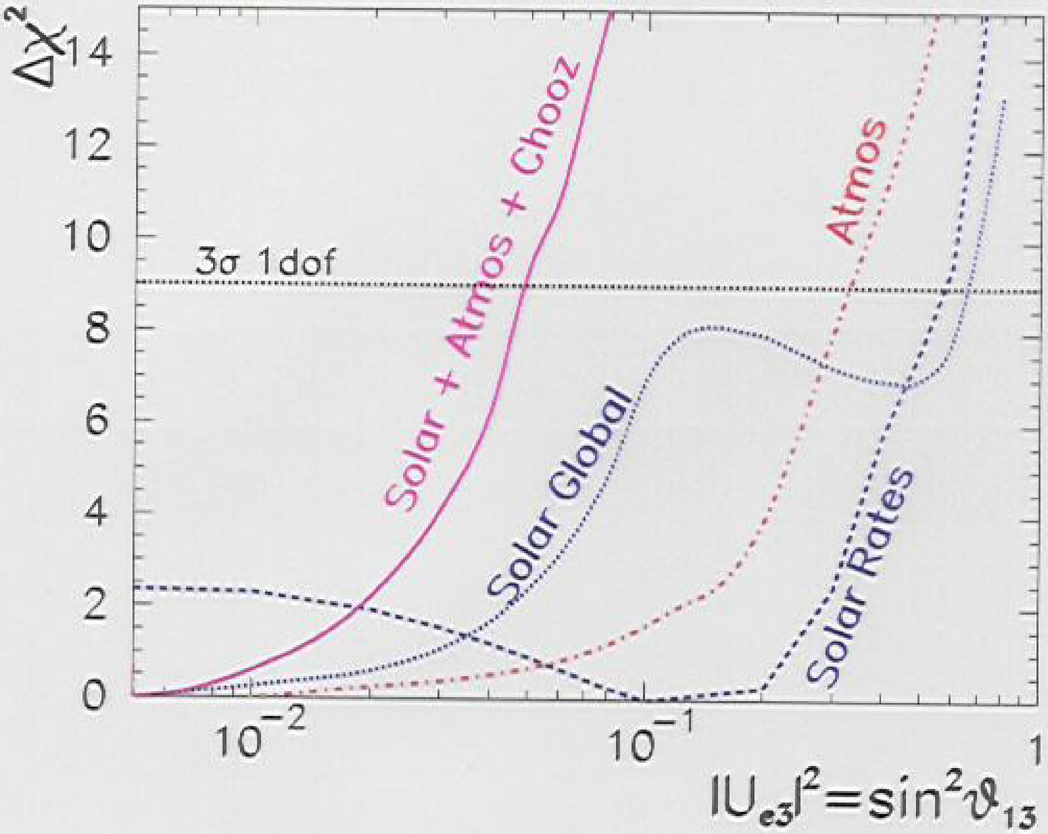
$$= \sum_i U_{ei}^2\, m_i \frac{(-i)}{(2\pi)^4} \int d^4p \frac{e^{ip(x_1-x_2)}}{p^2 + m_i^2} \frac{1-\gamma_5}{2} C$$

If m_i are small ($<$ MeV), they can be neglected in the propagator

$\Rightarrow$ Amp$[\beta\beta_{0\nu}] = \langle m_\nu \rangle$ (Ph. Sp.) (Nucl. Phys.)

$$\boxed{\langle m_\nu \rangle = \sum_i U_{ei}^2\, m_i}$$

3–ν Combined Analysis: Constraints on θ_{13}



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- 3σ (1dof) allowed ranges of parameters

$$
\begin{array}{rcl}
1.4\times10^{-3} < & \Delta m^2_{32}/\mathrm{eV}^2 & < 6\times10^{-3} \\
1.9\times10^{-5} < & \Delta m^2_{21}/\mathrm{eV}^2 & < 2.7\times10^{-4} \\
0.4 < & \tan^2\theta_{23} & < 3. \\
0.22 < & \tan^2\theta_{12} & < 0.71 \\
\sin^2\theta_{13} & < 0.05 &
\end{array}
$$

Mixing Matrix U

$$
U = \begin{pmatrix}
0.74-0.91 & 0.41-0.65 & <0.24 \\
0.21-0.64 & 0.25-0.77 & 0.51-0.87 \\
0.05-0.56 & 0.40-0.83 & 0.48-0.85
\end{pmatrix}
$$

- **KNOWN FACTS** (with care)

→ Sterile ν's not needed in the Mixing

→ $|\Delta m^2_{12}| \lll |\Delta m^2_{23}|$
Solar Atmospheric

→ Atmospheric ν oscillation compatible with $\nu_\mu \to \nu_\tau$: near maximal mixing

$$c_{23} \sim s_{23} \sim \frac{1}{\sqrt{2}}$$

$$|\Delta m^2_{23}| \sim (1.6-4)\times 10^{-3}\,eV^2$$

→ Solar ν oscillation compatible with LMA-MSW: near maximal mixing $\nu_e \to \nu'$

$$c_{12} \sim s_{12} \sim 1/\sqrt{2}$$

$$|\Delta m^2_{12}| \sim (2-30)\times 10^{-5}\,eV^2$$

→ CHOOZ reactor + Atmospheric

$$s^2_{13} \lesssim 0.05$$

- For $m_1 \ll m_2 \ll m_3$, $\Delta m_{12}^2 \frac{R}{2P} \ll 1$,

$$P_{\alpha \to \alpha'} = 2|U_{\alpha' 3}|^2 |U_{\alpha 3}|^2 \left(1 - \cos \Delta m_{31}^2 \frac{R}{2P}\right)$$
$\alpha' \neq \alpha$

$\Rightarrow$ **SAME FORM** as for 2ν, BUT different meaning of "mixing"

$$P_{\alpha\alpha} = 1 - \sum_{\beta \neq \alpha} P_{\alpha\beta} =$$
$$= 1 - 2|U_{\alpha 3}|^2 (1 - |U_{\alpha 3}|^2)\left(1 - \cos \Delta m_{31}^2 \frac{R}{2P}\right)$$

$\Rightarrow$ Disappearance Reactor Experiment gives $|U_{e3}|^2$: CHOOZ, Palo Verde

→ Zeroth Order Approximation

$$U = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

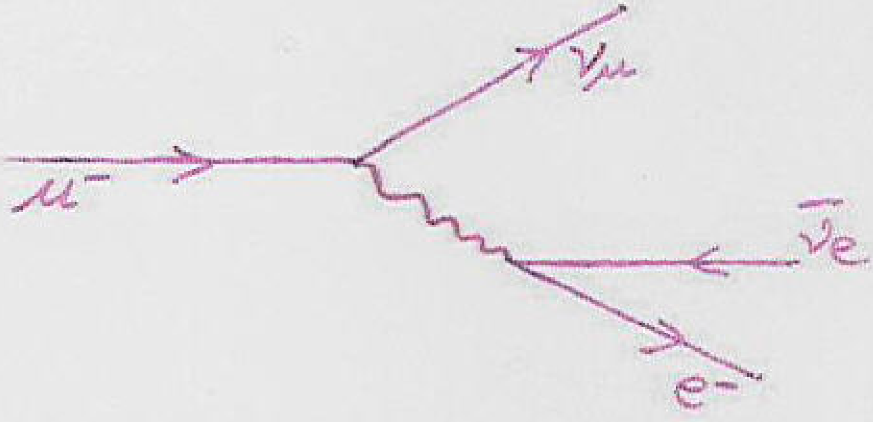
Main Question: U_{e3} ?

[to be answered <u>before</u> ν'Factories]

⇝ No ~~CP~~ - physics without $U_{e3} \neq 0$!

ν' FACTORIES

BEAM COMPOSITION



$\mu^- \longrightarrow \nu_\mu \; \bar{\nu}_e \; e^-$

$\bar{\nu}_e \to e^+$	DISAPPEARANCE
$\bar{\nu}_\mu \to \mu^+$	APPEARANCE
$\bar{\nu}_\tau \to \tau^+$	APPEARANCE
$\nu_e \to e^-$	APPEARANCE
$\nu_\mu \to \mu^-$	DISAPPEARANCE
$\nu_\tau \to \tau^-$	APPEARANCE

SEARCH FOR WRONG-SIGN μ

EXTREMELY SENSITIVE APPEARANCE MEASUREMENT

(Geer)

UNKNOWNS

- **Dirac or Majorana?**

  $m_\nu \neq 0$ without ν_R? $\rightarrow$ Mj

  Dimension 5 - Effective $\mathcal{L}$ in $SU(2) \times U(1)$

  "See-Saw" Mechanism

  $\beta\beta_{0\nu} \rightarrow \langle m_\nu \rangle \equiv \sum_i U_{ei}^2 m_i$

- **Absolute Masses**

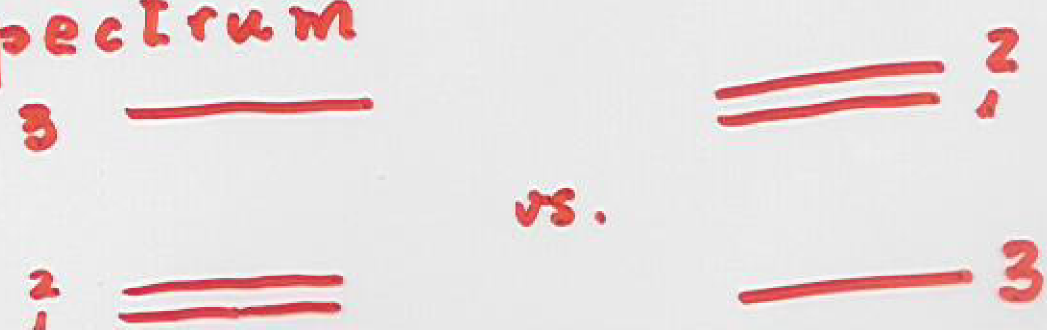
  Δm^2_{jk} $\oplus$ The most sensitive "Direct" Mass measure

  $\rightsquigarrow$ ^3H Beta Decay and/or SN

  $$m_\beta^2 \equiv \sum_i |U_{ei}|^2 m_i^2$$

  $\rightsquigarrow$ $\langle m_\nu \rangle$ in $\beta\beta_{0\nu}$

- **Spectrum**



- Follow the fathers of SM:

(AT PRESENT ENERGIES) $SU(2) \times U(1)$

with a particle content WITHOUT ν_R

- Is it possible (with only ν_L) to have $m_\nu \neq 0$?

A priori, YES $\longleftrightarrow$ Majorana

$$\mathcal{L}^{Maj}_{mass} = -\frac{1}{2}\, \bar{\nu}_L\, \underset{\sim}{M}\, \nu^c_L + h.c.$$

$SU(3)_{colour} \otimes U(1)_{e.m.}$ invariant $\Rightarrow$ legal

$\mathcal{L}^{Maj}$ + Pauli $\Rightarrow$ $M^T = M$

Diagonalization $\searrow$ $\downarrow$

$$\underset{\sim}{M} = U\, m\, U^T$$

$$\mathcal{L}^{Maj}_{mass} = -\frac{1}{2}\, \bar{\chi}\, m\, \chi$$

$$\chi \equiv U^+ \nu_L + (U^+ \nu_L)^c$$

$$\boxed{\begin{array}{c}\text{Majorana Field} \\ \chi = \chi^c = C\,\bar{\chi}^T\end{array}}$$

$\Rightarrow$ Neutrinos would be "true" neutrals

- NO conserved GLOBAL LEPTON NUMBER

$\Rightarrow$ $\beta\beta_{-0\nu}$ allowed

BUT ...

- $\mathcal{L}^{Maj}_{mass}$ cannot be GENERATED by SSB of a RENORMALIZABLE (dim. 4) Yukawa interaction! Higgs triplet?

1970's $\rightarrow$ 1990's: Requirement of RENORMALIZABILITY has a different PHILOSOPHY:

- Take particle content of SM and ask WHAT IS THE LOWEST DIMENSION (NON-RENORMALIZABLE) OPERATOR WITH $SU(2) \times U(1)$ GAUGE INVARIANCE?

UNIQUE dim. 5 $\Updownarrow$

$$\mathcal{L}_{eff} = -\frac{1}{2\Lambda}(\bar{\tilde{\ell}}_L \varphi) F (\tilde{\varphi}^+ \ell_L)$$

$$\tilde{\ell} = i\tau_2 \ell^c = i\tau_2 C \bar{\ell}^T$$

- The FIRST window to BEYOND SM
- $F = F^T$ matrix in flavour-space
- Coupling $\frac{1}{\Lambda} \Leftrightarrow \Lambda \equiv$ New Physics Scale

$\Rightarrow$ 1) $\Delta L = 2$

2) $F \Rightarrow$ Mixing, LFV

3) After SSB : $\mathcal{L}_{eff} \to \mathcal{L}^{Maj}_{mass}$

$$\boxed{M = \frac{v^2}{\Lambda} F}$$

"see - saw" type

Conclusion

$\mathcal{L}^{Maj}_{mass}$ for "light" neutrinos GENERATED from $\mathcal{L}_{eff}$ (at present energies).

- Origin of Λ ?
  1) Heavy mass ν_R ?
  2) Fierz - reordering

$$\mathcal{L}_{eff} = -\frac{1}{4\Lambda}\left(\bar{\tilde{l}}_L F \vec{\tau}\, l_L\right)\underbrace{\left(\tilde{\varphi}^+ \vec{\tau}\, \varphi\right)}$$

Higgs triplet?

- A particular example : SO(10) GUT

$\Rightarrow$ As part of SB , ν_R obtains a large Majorana mass Λ.

- The Dirac mass terms $\nu_R \leftrightarrow \nu_L \; m_D$ produce mixing of heavy ν_R into ν_L $\Rightarrow$ $m_\nu = \dfrac{m_D^2}{\Lambda}$

- "SEE-SAW" MECHANISM

$SU(2) \times U(1)$ gauge invariance
SM + ν_R in particle content

$\Rightarrow$ Not only L-R Dirac Mass, R Majorana Mass too

$$\mathcal{L}^{D-M} = -m_D \bar{\nu}_R \nu_L - \frac{1}{2} m_R \bar{\nu}_R (\nu_R)^c + h.c.$$

$$= -\frac{1}{2} (\bar{n}_L)^c M \, n_L + h.c.$$

$$n_L \equiv \begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix} , \quad M = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}$$

$\rightarrow$ For one family and $m_D \ll m_R$,

$$m_1 \simeq \frac{m_D^2}{m_R} , \quad m_2 \simeq m_R ,$$

$$\theta \simeq \frac{m_D}{m_R} ; \quad \eta_1 = -1 , \eta_2 = 1$$

$$\Rightarrow \boxed{\nu_L \simeq -i \, \nu_{1L} , \quad (\nu_R)^c \simeq \nu_{2L}}$$

ν_1, ν_2 Majorana Fields

- Majorana Fields

$$\nu_1 \simeq i\,\nu_L - i\,(\nu_L)^c \; ; \quad \nu_2 = \nu_R + (\nu_R)^c$$

1 light neutrino $\quad m_1 \ll m_D$

+

1 heavy neutrino $\quad m_2 \gg m_D$

→ $m_L = 0 \Leftrightarrow$ Global L violated only by $-\frac{1}{2} m_R \overline{\nu}_R (\nu_R)^c$ characterized by large mass.

→ $m_D \simeq \mathcal{O}$(quark, lepton) mass

$$\boxed{\begin{array}{c}\text{SMALLNESS OF NEUTRINO MASS} \\ \longleftrightarrow \text{L-VIOLATION at } m_R \simeq M_{GUT}\end{array}}$$

- For 3 families, $\quad m_i \simeq \dfrac{(m_f^i)^2}{M_i} \ll m_f^i$

1) ν_α with definite mass → Majoranas
2) 3 "active" massive neutrinos
3) Hierarchy of masses $m_1 \ll m_2 \ll m_3$.

$$H = \frac{1}{2E}\left\{ U \begin{pmatrix} 0 & & \\ & \Delta m^2_{12} & \\ & & \Delta m^2_{13} \end{pmatrix} U^+ + \begin{pmatrix} a & & \\ & 0 & \\ & & 0 \end{pmatrix} \right\}$$

⇝ Interference with MEDIUM Effects sees the SIGN.

⇝ $\nu \to \bar{\nu}$: $U \to U^*$, $a \to -a$

Suggestion:

Muon-Charge Asymmetry for Atmospheric Neutrinos from below

$$\frac{(\nu_{atm} \to \nu_\mu) - (\bar{\nu}_{atm} \to \bar{\nu}_\mu)}{+}$$

⇝ Magnetized Iron: MINOS, MONOLITH, ...

But ... $\gtrsim$ 100 Kton

→ U_{e3}:

Appearance $\nu_e \to \nu_\mu \sim U_{e3}$ better than Disappearance

→ δ : ν' FACTORIES

$(\nu_e \to \nu_\mu) - (\bar{\nu}_e \to \bar{\nu}_\mu) \longleftrightarrow$ ~~CP~~ + $a \neq 0$

or SUPERBEAMS $(\nu_\mu \to \nu_e)$

CONCLUSIONS

- Exciting times in ν'Physics.
- Convincing and Consistent Evidence for ν'Oscillation in

  Atmospheric : $\Delta m^2_{23} \oplus \theta_{23} \simeq \frac{\pi}{4}$

  $\oplus$

  Solar : $\Delta m^2_{12} \oplus \theta_{12} \simeq \frac{\pi}{4}$
- Test of Atmospheric by LBL.
- Test of Solar by BOREXINO plus Reactor Exp. KAMLAND.
- $\theta_{13} \rightsquigarrow$ Appearance $\nu_\mu \rightleftarrows \nu_e$.
- $\delta \rightsquigarrow \cancel{CP}, \cancel{T}$
- Sign $[\Delta m^2] \leftrightarrow$ Interference with Medium Effects
- Above all, THEORY expects ν's are MAJORANA particles