THEORETICAL ISSUES WITH MASSIVE AND MIXED NEUTRINOS

Les H. June 2001

LARGE MIXING IS AN OLD STORY IN ν-PHYSICS

ν - PHYSICS WAS OFTEN ...

½ RIGHT + ½ WRONG

examples:

- continuous β-spectrum
- Pauli's letter
- Premature Oscillations ...

- ν's HISTORICAL RÔLE IN WEAK INTERACTIONS
- ν's & THE STANDARD MODEL
- ν - MASSES
  - LEPTOHIGGS
  - GRAND UNIFIED MODELS
  - EXTRA ABELIAN REMNANTS
  - OFF THE WALL ?
- ν - MIXINGS : CONFRONTING "LARGE" MIXINGS

  "(PUTTING ON SNO-SHOES)"
- IMPLICATIONS

The Father Of The Neutrino

- Wolfgang Pauli Jr.
  Austrian Physicist
  1900-1957
- At 19, he wrote a review of Einstein's Theory of General Relativity!
- He was awarded the Nobel Prize in 1945

GREAT *DATES* in HISTORY

- Dear Radioactive Ladies and Gentlemen:
- I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the energy theorem. … there could exist in the nuclei electrically neutral particles… which have spin ½, and …do not travel with the velocity of light. The continuous beta spectrum would then become understandable.
- …I do not feel secure enough to publish anything about this idea… but only those who wager can win…

- Written a few days after divorcing actress Kate Deppner
- Within a year Pauli was under analysis with C. Jung!

- One particle solves two problems

- Chadwick discovers a heavy nuclear particle: the NEUTRON, solving Pauli's "exchange" problem

It's a… Neutrino!

- Enrico Fermi, Italian Physicist, 1901-1954

- He called Pauli's particle the "little neutron", in Italian, neutrino
- He was awarded the Nobel Prize in 1938

NEUTRINOS IN THE STANDARD MODEL

ν_{Li} $i = 1, 2, 3$ PART OF ISODOUBLET
$i = e, \mu, \tau$

$I_W = \frac{1}{2}$ $(I_W)_3 = \frac{1}{2}$ $L_i = 1$

ONLY POSSIBLE MASS TERM : MAJORANA MASS *

$\nu_i^T \nu_j$ $I_W = 1$ ISOTRIPLET

$(I_W)_3 = +1$

$L_i + L_j = 2$

- NO TREE-LEVEL NEUTRINO MASS

(no HIGGS ISOTRIPLET WITH $\Delta L = -2$)

AT QUANTUM LEVEL, CAN GENERATE

$$\frac{1}{M} \nu_i^T \vec{\tau} \nu_j H \vec{\tau} H$$

INVARIANT UNDER $SU_2 \times U(1)$

WHAT IS M?

BUT HAS $L_i + L_j = 2$

STANDARD MODEL NEUTRINO MASS FORBIDDEN

ONLY BY

CHIRAL GLOBAL SYMMETRIES : LEPTON NUMBERS

- total lepton number $L \equiv L_e + L_\mu + L_\tau$

  $\rightarrow$ (B-L by anomalies)

- relative lepton numbers $L_e - L_\mu$, $L_\mu - L_\tau$

$$\boxed{m_\nu \neq 0 \implies \text{PHYSICS BEYOND STANDARD MODEL}}$$

WHAT KIND OF PHYSICS ?

CAN NEUTRINO MASSES AND MIXING

GIVE US A HINT ?

MASSIVE NEUTRINOS

REQUIRE

NEW PARTICLES

must go ...

<u>Beyond the Standard Model</u> !

masses must be small !

NEW PARTICLES ARE :

HIGGS-LIKE (scalars)

"lepto-higgs"

carry lepton number

couple to $(\psi\psi)_{SM}$

FERMIONS

Sterile neutrinos

carry lepton number

couple to $(\psi H)_{SM}$

THEY LIVE IN :

3 SPACE DIMENSIONS

OR

4 OR MORE SPACE DIMENSIONS (ONLY IF STANDARD-MODEL SINGLETS ?)

(ADD, DDG) (not inclusively)

LEPTONIC HIGGS

- INTRODUCE NEW HIGGS WITH LEPTON NUMBER
- THEIR INTERACTIONS BREAK LEPTON NUMBER

EXPLICITLY , or SPONTANEOUSLY

↓

MASSIVE (MAJORANA) NEUTRINOS

YUKAWAS:

$L_i \vec{\tau} L_j \cdot \vec{T}$ — family symmetric; isotriplet

$-1 \quad -1 \quad +2$

$L_i\, L_j\, S^{+}$ — family antisymmetric; isosinglets

$-1 \quad -1 \quad +2$

$\bar{e}_i\, \bar{e}_j\, S^{--}$ — isosinglets

$2 \quad 2 \quad -4$

$S^{+} S^{+} S^{--}$

$\vec{T} \cdot \vec{T}\; S^{--}$

$H \vec{\tau} H \cdot \vec{T}$

ALL INVARIANTS VIOLATE LEPTON NUMBER

↓

MAJORANA NEUTRINO MASSES

STERILE NEUTRINOS

INTRODUCE NEW FERMIONS WITH NO STANDARD MODEL CHARGES

BUT CARRY LEPTON NUMBER THROUGH COUPLING WITH

$$L_i \, H \cdot \bar{N}_k \qquad k = 1, 2, \ldots N_s$$

lepton # $\quad l_i + 0 \quad + (-l_i) = 0$

WHAT ARE THESE FERMIONS ? ("who ordered them?")

mass ?

habitat ?

how many ?

MASSES

STANDARD MODEL AS AN EFFECTIVE THEORY

$M\ (\bar{N}\ \bar{N})$ • M UNCONSTRAINED BY QUANTUM NUMBERS

• $M = 0$ ENFORCED BY LEPTON NUMBER

$M \neq 0$ BREAKS LEPTON NUMBER

$M \sim$ CUT-OFF OF STANDARD MODEL

$\boxed{\nu\text{-MASS MEASURES THE STANDARD MODEL CUT-OFF}}$

mass matrix

$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

$m \lesssim 200$ GeV

eigenvalues ($M \neq 0$)

$$\frac{M}{2} + \sqrt{\frac{M^2}{4} + m^2} \qquad \frac{M}{2} - \sqrt{\frac{M^2}{4} + m^2}$$

• $M \sim m$:

LARGE NEUTRINO MASSES

• $M \gg m$ 

light $\sim$ $m\left(\frac{m}{M}\right)$ SCALE RATIO SUPPRESSION

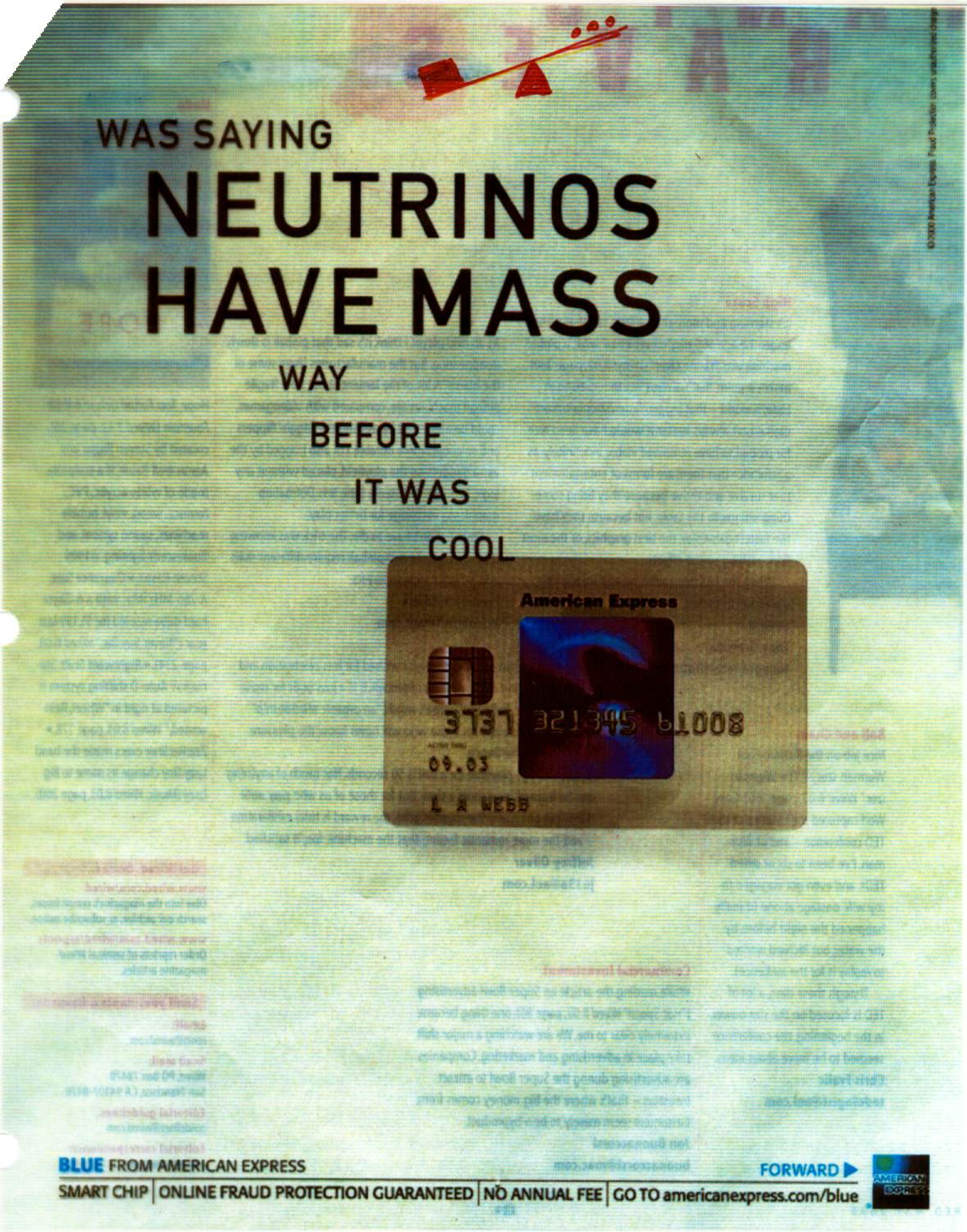
heavy $\sim$ M

ν - MASS : $\longrightarrow$ $\dfrac{\text{SCALE OF EW BREAKING}}{\text{STANDARD MODEL CUT-OFF}}$

$m_\nu \sim$ meV $\longrightarrow$ CUT-OFF $\gtrsim 10^{15}$ GeV (error in exponent)

UNIFICATION OF COUPLINGS WITH SUPERSYMMETRY ALSO YIELDS 10^{15} GeV!

TRUTH OR COINCIDENCE ?



WAS SAYING
NEUTRINOS
HAVE MASS
WAY
BEFORE
IT WAS
COOL
American Express
09.03
L A WEBB
BLUE FROM AMERICAN EXPRESS
FORWARD ▶
SMART CHIP | ONLINE FRAUD PROTECTION GUARANTEED | NO ANNUAL FEE | GO TO americanexpress.com/blue

- $M = 0$ STRICT LEPTON # CONSERVATION

$L_i H \bar{N}$ $\longrightarrow$ DIRAC MASS

how come it is so small ?

- $M \sim 0$

which quantum numbers keep it close to zero ?

FIELDS IN HIGHER DIMENSION

KINETIC TERMS

	$\int dx$	$\bar\Psi$	$\not\partial$	Ψ	$\int dx$	$\partial\bar\Phi$		$\partial\Phi$	
3+1	-4	$3/2$	1	$3/2$	-4	1	1	1	1
4+1	-5	2	1	2	-5	1	$3/2$	1	$3/2$

⋮

COUPLING IN 4-DIMENSIONS

$$\int d^4x \; L \, H \, \frac{\bar N_5}{\sqrt{M}} \qquad\qquad \int d^4x \; H^3 \frac{\Phi_5}{\sqrt{M}}$$

$$\bar N_5 = \frac{1}{\sqrt{2\pi R}}\left(\bar N_4 + \cdots\right) \qquad\qquad \Phi_5 = \frac{1}{\sqrt{2\pi R}}\left(\varphi_4 + \cdots\right.$$

$$\rightarrow \frac{1}{\sqrt{MR}} \quad \text{suppression}$$

if $MR \gg 1$

KALUZA- KLEIN TOWERS

ν_{n+1} - - - - - - - - - $\sqrt{\mu_e^2 + \frac{(n+1)^2}{R^2}}$

ν_n - - - - - - - - - $\sqrt{\mu_e^2 + \frac{n^2}{R^2}}$

$\vdots$

ν_1 - - - - - - - - - $\sqrt{\mu_e^2 + \frac{1}{R^2}}$

ν_0 - - - - - - - - - μ_e

KKT

$$\int d^4x \; \frac{1}{\sqrt{MR}} \; L_i H_u \bar{N}_k \quad + \int d^5x \; \mu \bar{N}\bar{N}$$

added suppression

geometric factor

bulk mass term

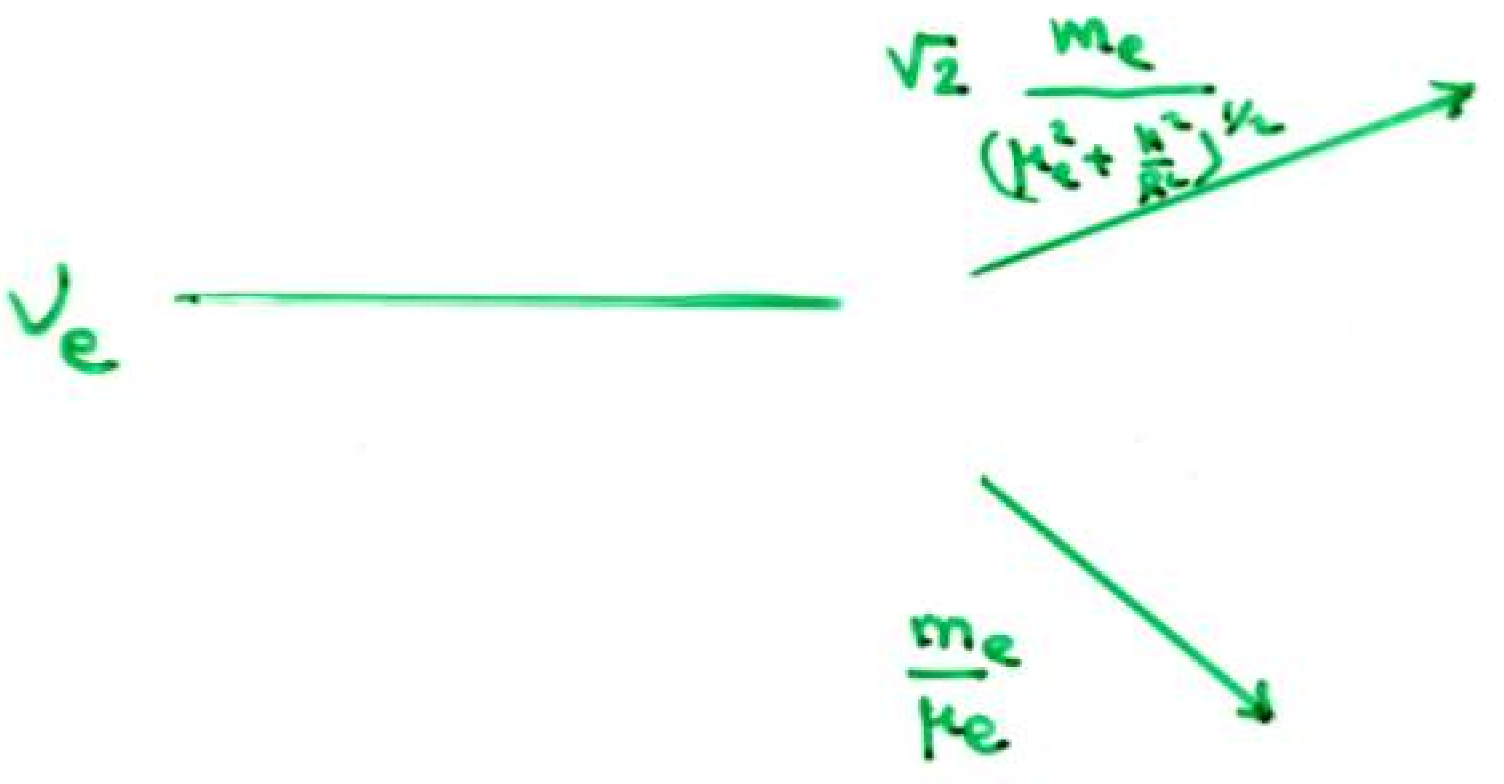
KEPT SMALL BY ?

SMALL NEUTRINO MASSES TIED TO

BULK PHYSICS

" A NEUTRINO ON THE BRANE IS BETTER THAN

TWO IN THE BULK "



Large angle $\nu_e \to \nu_{KK}$ as explanation of solar neutrino anomalies

TO DIFFERENTIATE BETWEEN THESE DIFFERENT

THEORETICAL CHOICES,

WE NEED MORE INFORMATION

ν- MASS HIERARCHIES

ν- MIXING PATTERNS

OBSERVABLE NEUTRINOS

WHAT DO EXPERIMENTS TELL US?

THOSE FUNNY NEUTRINOS!

① NUMBER OF ν_μ's FROM COSMIC RAY COLLISION WITH ATM IS BELOW EXPECTATIONS AND CORRELATES WITH OSCILLATIONS OF $\nu_\mu \to \nu_\tau$ WITH LARGE (maximal?) MIXING!

$$|m^2_{\nu_\mu} - m^2_{\nu_\tau}| \sim 3 \times 10^{-3}\ eV^2$$

② EVIDENCE FOR $\bar{\nu}_\mu \to \bar{\nu}_e$ OSCILLATIONS AT LSND LARGE Δm^2

③ NUMBER OF ν_e's FROM THE SUN IS BELOW THEORY$_\odot$

BUT... ALL PREDICTED BY $\odot$ COME TO EARTH,

EXCEPT THAT SOME CHANGE FLAVOR ON THE WAY!

- FIRST SOLID EVIDENCE FOR OSCILLATIONS IN $\nu_\odot$!
- SMALL IF ANY STERILE ν'
- LARGE MIXING OF ν_e HINTED

TRUE CINDIRELLA STORY 

AFTER SNO, NATURE SETTLES DOWN:

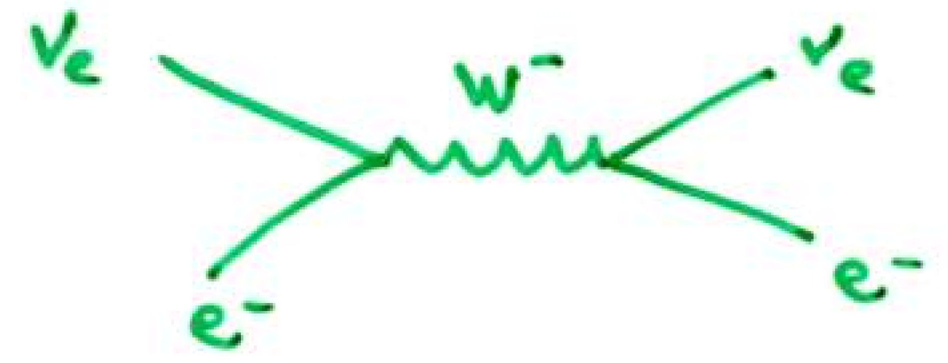
- 3 FLAVORS WITH LARGE MIXINGS (no sterile except for LSND)
- Δm^2 $10^{-3}\ eV^2 \to 10^{-12}\ eV^2$ very small.

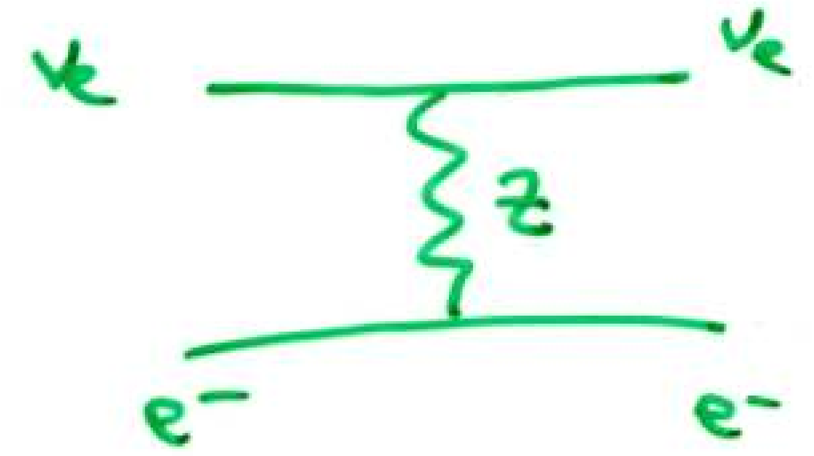
SOLAR NEUTRINOS

experiments over whole range of energies

Chlorine, Gallex, Sage –

A SUPERK : $\nu_e + e^- \to \nu_e + e^-$





conclusions : detect no spectral distortion of ^8B spectrum

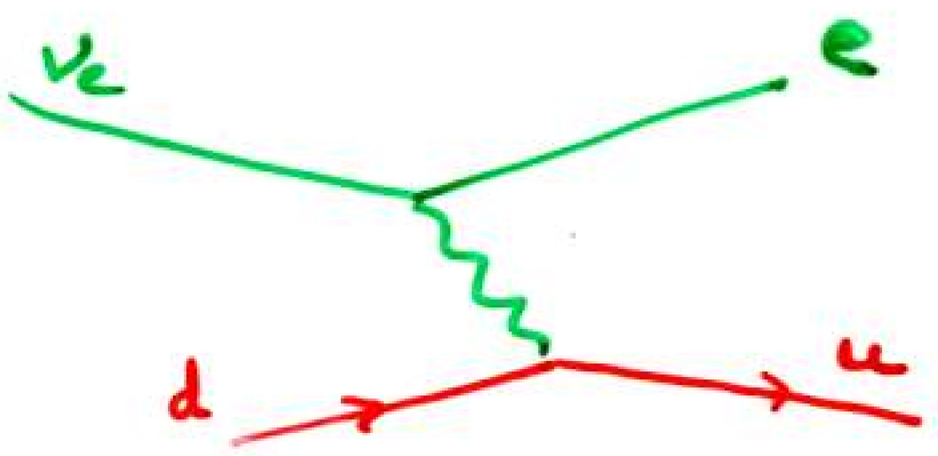
$\to$ favor large angle oscillations

small angle disfavored, but picture is confusing because of other data (e.g. day-night)

picture could be confirmed by KAMLAND.

(8) SNO

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



DATA NEXT MONTH !

- COMPARISON WITH SUPERK : HOW MUCH NEUTRAL CURRENT?
- MEASURE ^8B SPECTRUM DISTORTION

⋮

WILL EVENTUALLY MEASURE NEUTRAL CURRENT THROUGH

$$\nu_e + D \to p + n + \nu$$

(install neutron catchers)

LSND

LARGE Δm^2 FOR $\bar{\nu}_\mu \rightsquigarrow \bar{\nu}_e$

TO BE TESTED AT FERMILAB VIA MINIBOONE EXPT.

SOON.

IMPLICATIONS

- IF ALL EXPTS ARE "RIGHT" THERE MUST BE A FOURTH NEUTRINO.
- IT MUST BE AN EW SINGLET (Γ_Z WELL MEASURED)

THEORY:

IF THERE IS A FOURTH NEUTRINO,

WHY IS IT LIGHT since it has no EW charge.

WHY DOES IT COUPLE?

WHY DIFFERENT Δm^2.

NEW SYMMETRIES IN NEUTRINO MASS MATRIX NOT FOUND IN QUARKS AND CHARGED LEPTONS?

WHAT ARE THE STERILE NEUTRINOS?

- ONE OF THE BOYS?

  Grand · Unified

  Abelian symmetries

- OUT OF THIS (BRANE) WORLD

  Modulini ?

NEED TO EXPLAIN

smallness of masses

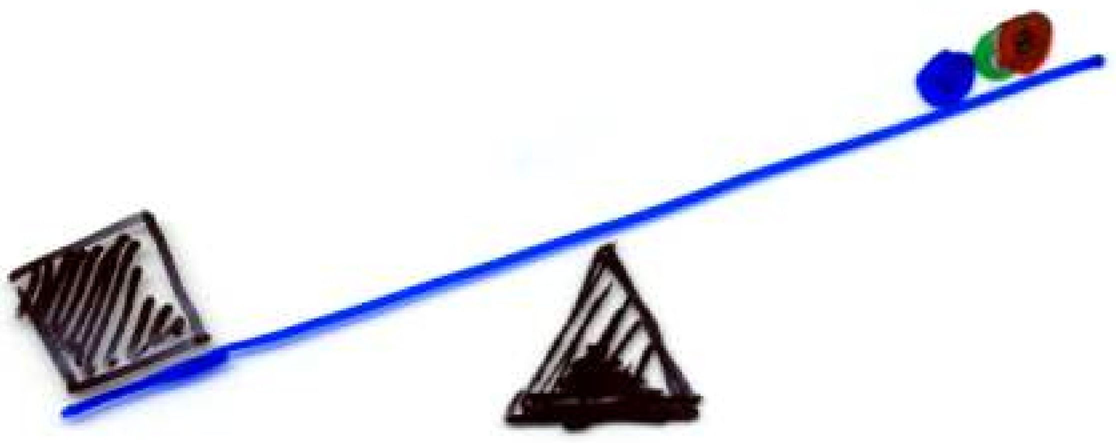
mixing angles : large $\nu_\mu - \nu_\tau$

? large $\nu_e - \nu_\mu$ $\cancel{\nu_e - \nu_s}$

? small $\cancel{\nu_e - \nu_\mu}$ $\cancel{\nu_e - \nu_s}$

SNO-ed under

FACING LARGE MIXINGS



THE PROBLEM :

QUARKS & LEPTONS ARE ON THE SAME LEVEL

anomalies, GUTS , ...

QUARKS : • hierarchy of masses in each charged sector

• two mixing $\mathcal{U}_{2/3}$, $\mathcal{U}_{-1/3}$

one observable CKM: $\mathcal{U}^{\dagger}_{2/3}\,\mathcal{U}_{-1/3} = 1 + \mathcal{O}(\lambda_c)$

Cabibbo angle

$\rightarrow \quad \alpha_{2/3} - \alpha_{-1/3} = 0 \mod(\frac{\pi}{2}) + \cdots$

$\boxed{\text{in limit } \lambda_c \rightarrow 0}$

probably in that limit : 2 massless quarks in each charge sector.

LEPTONS

- hierarchy of charged leptons
- possible hierarchy of neutrinos
- two mixings $\mathcal{U}_{-1}$, $\mathcal{U}_0$

one observable, MNS(P) : $\mathcal{U}_{-1}^{\dagger}\mathcal{U}_0$

but SK + SNO $\rightarrow$ $\mathcal{U}_{-1}^{\dagger}\mathcal{U}_0$ = "near maximal mixing"

$$\alpha_{-1} - \alpha_0 = \frac{\pi}{4} \quad \mathrm{mod}\left(\frac{\pi}{2}\right)$$!!

IF $\lambda_c \rightarrow 0$ APPLIES TO LEPTONS,

IN THAT LIMIT NEUTRINOS MIX ! (A LOT)

IS THIS A PROBLEM?

EXAMINE THE PROBLEM IN THE FOLLOWING :

- LIMIT WHERE TWO FAMILIES ARE MASSLESS
- LIMIT WHERE ONE FAMILY IS MASSLESS + HIERARCHY FOR OTHERS

START WITH QUARK YUKAWA MATRICES

$$\begin{array}{cc} & \bar{u} \\ Q & \begin{pmatrix} \lambda^8 & \lambda^{4+1} & \lambda^{0+3} \\ \lambda^7 & \lambda^4 & \lambda^{0+2} \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix} \end{array}$$

$$\text{CKM} \sim \begin{pmatrix} 1 & \lambda^1 & \lambda^3 \\ \lambda^1 & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\begin{array}{cc} & \bar{d} \\ Q & \begin{pmatrix} \lambda^4 & \lambda^{2+1} & \lambda^{0+3} \\ \lambda^3 & \lambda^2 & \lambda^{0+2} \\ \lambda & 1 & 1 \end{pmatrix} \end{array}$$

$\lambda_c \rightarrow 0$:

$$m^{(2/3)} \longrightarrow \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad u, c \text{ massless}$$

$$m^{(-1/3)} \longrightarrow \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \alpha & \beta \end{pmatrix} \quad d, s \text{ massless}$$

α, β order 1.

WHAT ABOUT LEPTONS ?

HAVE TO GUESS

i.e. INVOKE DEEP THEORY

FIRST GUESS $\quad SU_5 \; , \; SO_{10}$ naïve.

SU_5 : $\quad m^{(-1/3)} = m^{(-1)\,t}$

CHARGED LEPTON MATRIX $= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \alpha \\ 0 & 0 & \beta \end{pmatrix}$ two massless e^-, μ^-

$$\mathcal{U}_{-1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \qquad \tan\theta = \frac{\alpha}{\beta} \sim 1$$

to get $\mathcal{U}_0$, need 

$$m^{\nu\nu} = m^{(0)} \frac{1}{M} m^{(0)\,t}$$

(M that is left as $\lambda \to 0$)

SO_{10} : $\quad m^{(2/3)} \sim m^{(0)} \; : \; m^{(0)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$

$$\to \quad m^{(\nu\nu)} = \frac{m^2}{M} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \text{massless } \nu_1, \nu_2$$

$$\Rightarrow \quad \mathcal{U}_0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

MNSP : $\quad \mathcal{U}^\dagger_{-1} \mathcal{U}_0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \longrightarrow$ order 1 mixing!

LARGE ~ NOT CABIBBO-SUPPRESED MIXING OF HEAVIEST ν

- NOT UNEXPECTED, 1982 $\rightarrow \dots$
- GENERATED BY THE CHARGED LEPTON MIXINGS

OTHER SCHEMES :

$$m^{(-1)} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad U_{-1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\rightarrow$$

$$m^{(0)} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix} \qquad U_0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c & s \\ 0 & -s & c \end{pmatrix}$$

mixing comes from ν-mass matrix

WHAT ABOUT THE MIXING BETWEEN

ν_1 AND ν_2 ? ($\nu_\odot$)

TURN ON PERTURBATION THAT GIVES MASS

TO SECOND FAMILY.

need to use degenerate perturbation theory

→ relative magnitude of entries in perturbation

yield the mixing.

example:

charge $-1/3$:

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 1 \end{pmatrix} + \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda & 0 & 0 \end{pmatrix} \begin{array}{l}]\; 3-2=1 \quad \mathcal{O}(\lambda) \quad 1\text{-}2 \\ ]\; 2 \quad \mathcal{O}(\lambda^2) \quad 2\text{-}3 \end{array} \quad \text{etc...}$$

below diagonal
gives $\bar{d}$ mixing : physically not there.

SU_5 : $\quad m^{(-1/3)} \sim m^{(-1)}$

$$\mathcal{U}_{-1} = \begin{pmatrix} 1 & \text{small} & \text{small} \\ \text{small} & \cos\theta & \sin\theta \\ \text{small} & -\sin\theta & \cos\theta \end{pmatrix}$$

$\mathcal{U}_{-1}$ GENERATES SMALL MIXING

BETWEEN $\nu_e - \nu_\mu, \nu_\tau$

WHAT ABOUT $\mathcal{U}_0$?

$\mathcal{U}_0$ DIAGONALIZES $\quad m^{(\nu\nu)} = m^{(0)} \frac{1}{M} m^{(0)t}$

SO_{10} : $\quad m^{(0)} \sim m^{(2/3)}$ in terms of perturbations

$\bar{5} \cdot 1 \quad 10 \cdot 10 \quad \rightarrow \mathcal{U}_0$ small angles

or

$[\,16 \cdot 16 \quad 16 \cdot 16\,]$

TO GET LARGE MIXINGS IN $\mathcal{U}_0$:

- change relation between $m^{(0)}$ and $m^{(2/3)}$

- appeal to special properties of seesaw form
  play on M ...

OR ... ABANDON SIMPLE-MINDED GUT RELATIONS

FROGGATT-NIELSEN APPROACH

WITH 

FIELDS ARE ASSIGNED U(1) CHARGES

YUKAWA OPERATORS ARE SMALLER THAN OTHERS BECAUSE THEY HAVE LARGER CHARGES

SEESAW + FN

$$\begin{pmatrix} L & \bar{N} \end{pmatrix} \begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix} \begin{pmatrix} L \\ \bar{N} \end{pmatrix}$$

$$= \begin{pmatrix} L E_L & \bar{N} E_{\bar{N}} \end{pmatrix} \begin{pmatrix} 0 & \hat{m} \\ \hat{m}^T & \hat{M} \end{pmatrix} \begin{pmatrix} E_L L \\ E_{\bar{N}} \bar{N} \end{pmatrix}$$

$E_{\bar{N}}$, E_L = diagonal matrices that contain whole suppression

for $\hat{m}$, $\hat{M}$ contain only elements of same order within each one.

$$\rightarrow \quad m^{(\nu\nu)} = L E_L \, \hat{m} \frac{1}{\hat{M}} \hat{m}^T E_L \, L$$

IN FN SCHEME, SUPPRESSION DEPENDS ONLY ON THE CHARGED LEPTON DOUBLETS U(1) CHARGES

SUPPRESSION PATTERN IN $\mathcal{U}_{-1}$

SAME AS IN $\mathcal{U}_0$!!!

MAXIMAL MIXINGS IN MNSP TELLS US:

THE THREE LEPTON DOUBLETS

HAVE THE SAME U(1) CHARGES

IMPLICATIONS:

- CHARGED LEPTON HIERARCHIES COME FROM

  DIFFERENT U(1) CHARGES FOR $\bar{e}_1, \bar{e}_2, \bar{e}_3$

- APPEARANCE OF EXTRA ABJ ANOMALIES!

  ↳ NEW PARTICLES ...

THIS IMPLIES

$$m^{(-1)} \sim \begin{pmatrix} \lambda^7 & \lambda^2 & 1 \\ \lambda^7 & \lambda^2 & 1 \\ \lambda^7 & \lambda^2 & 1 \end{pmatrix}$$

$$m \sim 1 \quad \lambda^2 \quad \lambda^7$$

$$\frac{m_\mu}{m_\tau} \quad \frac{m_e}{m_\tau}$$

BUT ANOMALY ARE CREATED ...

THIS APPROACH DOES NOT

IMPLY MAXIMUM MIXING

IT SIMPLY SAYS THAT MNSP MIXINGS

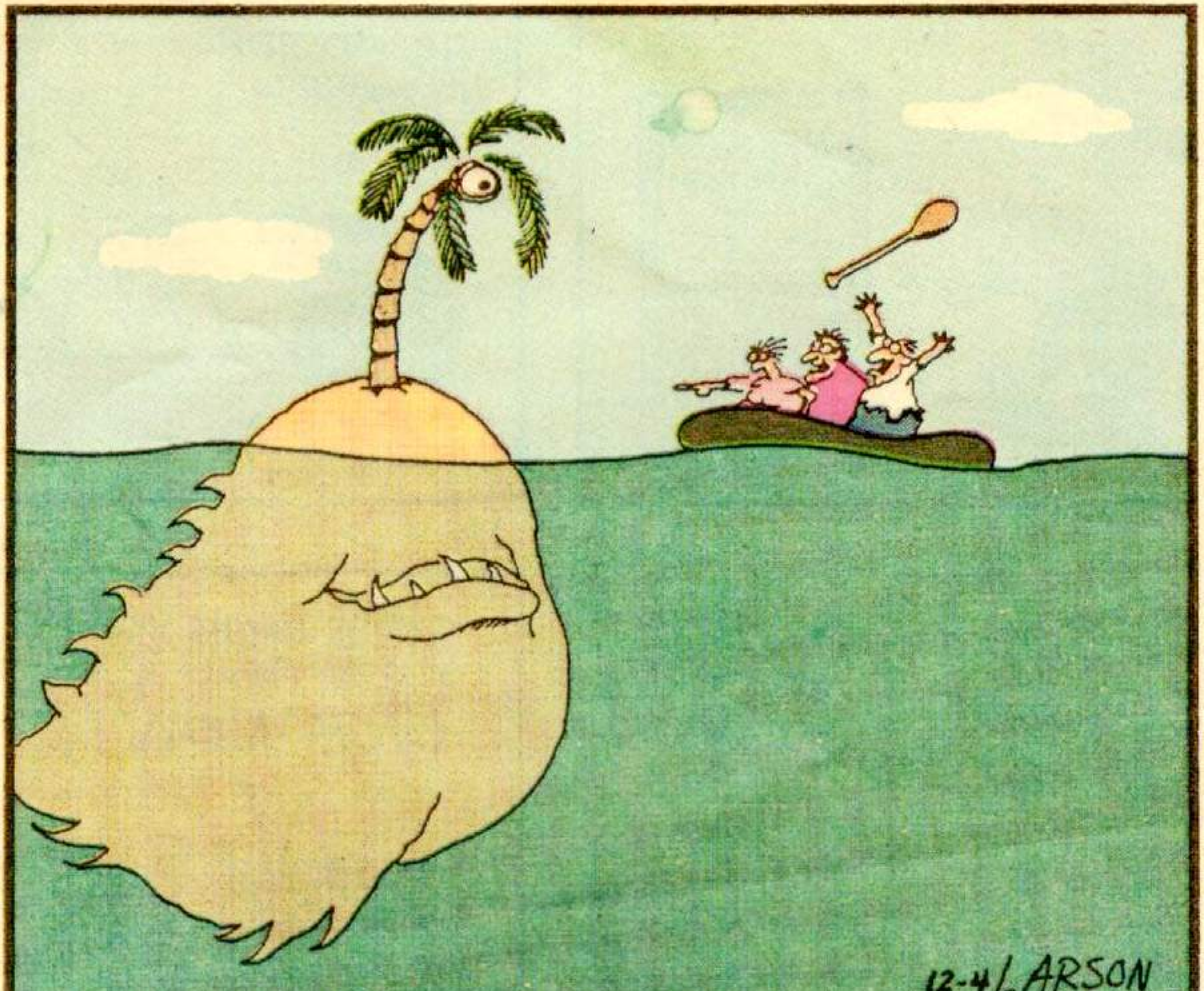
ARE NOT CABIBBO-SUPPRESSED .

CONCLUSIONS

- LOSS OF LIGHT STERILE ν IS WELCOME
- TWO LARGE MIXINGS IN MNSP MATRIX :
  - NAIVE GUT RELATIONS NEED TO BE CHANGED, ALTHOUGH ONE "LARGE" MIXING IS GUT-FRIENDLY
  - FROGGATT-NIELSEN APPROACH CAN ACCOMODATE TWO LARGE MIXINGS BUT AT THE COST OF ADDING EXTRA STUFF
  - SECOND LARGE MIXING MAY BE INDICATIVE OF RIGHT-HANDED MASS MATRIX PROPERTY ?

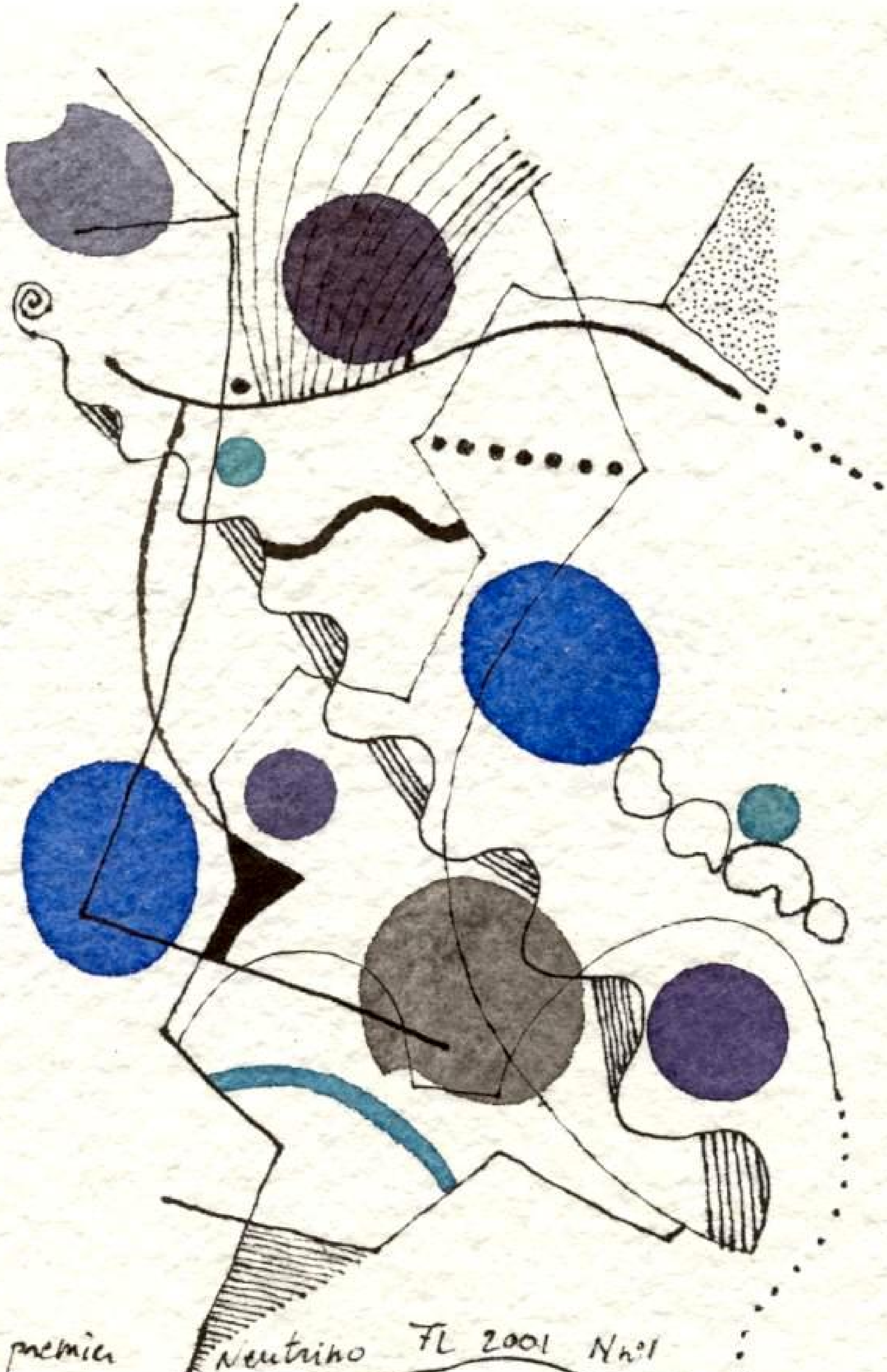
AFTER SNO, THEORISTS NEED TO SHOVEL THEIR DRIVEWAYS !..

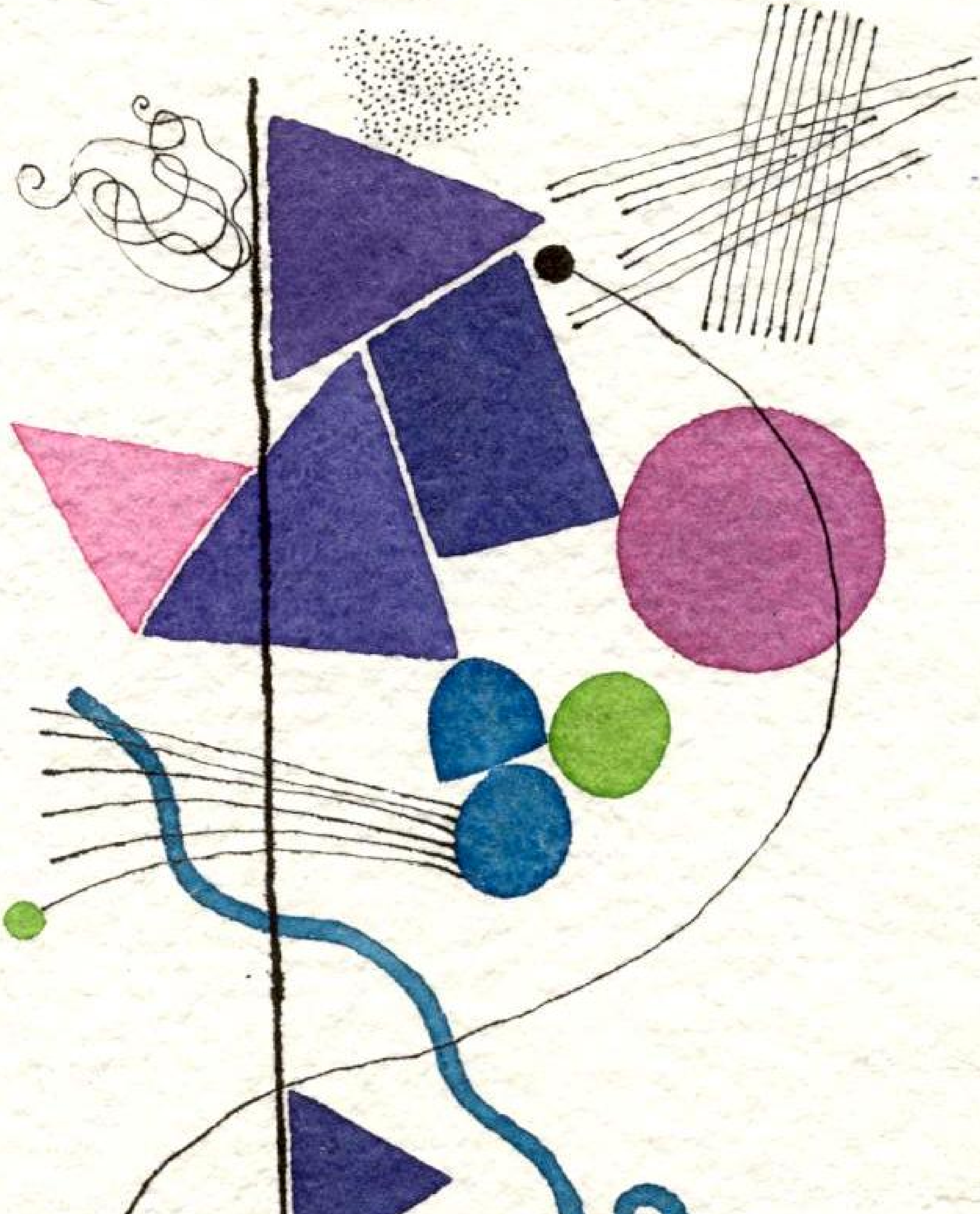
By GARY LARSON



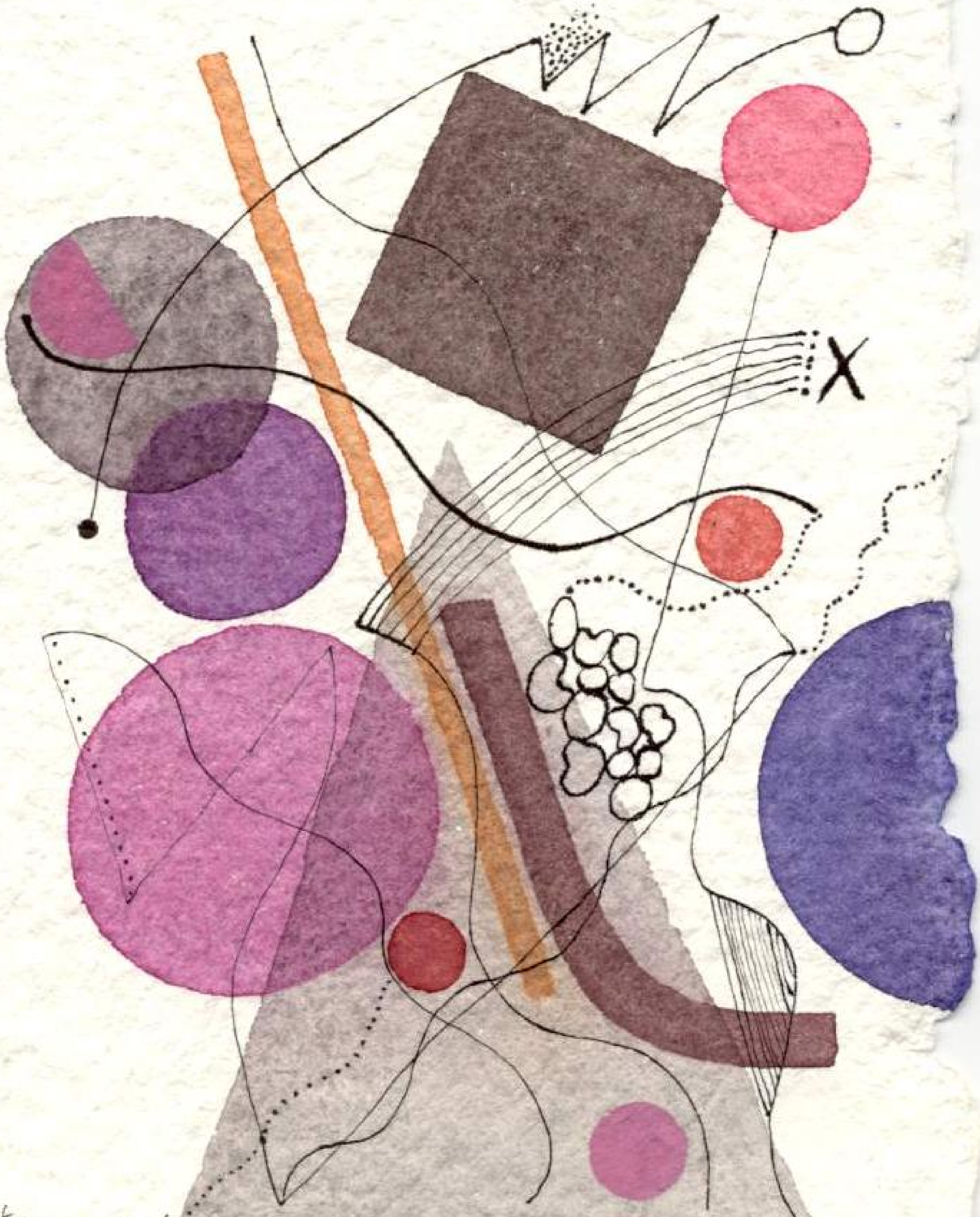
GREAT *DATES* in HISTORY

- Dear Radioactive Ladies and Gentlemen:
- I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the energy theorem. … there could exist in the nuclei electrically neutral particles… which have spin ½, and …do not travel with the velocity of light. The continuous beta spectrum would then become understandable.
- …I do not feel secure enough to publish anything about this idea… but only those who wager can win…


Mon premier Neutrino FL 2001 N°1



neutrino volage FL 2001 N°2



neutrino coincé dans un tango argentin FL 2001 No 5