Physics Beyond the Standard Model

First sign - Neutrino Mass

Possibilities:

1. Add $\nu_R \rightarrow \nu_L \nu_R \varphi$

$\rightarrow$ Usual Dirac masses

Problem: Largest $m_\nu < 10^{-6} m_e$

2. New physics at large scale $M \rightarrow$

$\nu_L \nu_L \varphi \varphi / M$

$\rightarrow$ Majorana masses $\sim \frac{v^2}{M}$

3. add ν_R with a large Majorana mass $M_R \rightarrow$

$$\begin{pmatrix} & m_D \\ m_D & M_R \end{pmatrix} \rightarrow$$

Majorana mass $\sim \frac{m_D^2}{M_R}$

See-saw formula

THEORETICAL MOTIVATION

QUARK-LEPTON SYMMETRY

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

1. Three generations
2. Mass hierarchy
3. Same weak interactions

If symmetry becomes exact → ν mass

ν_{Ri} must exist

GM-R-S solution: when symmetry is broken ν_R gets mass

$$m_\nu \sim \frac{m_D^2}{M}$$

$$\begin{matrix} & L & R \\ L & 0 & m_D \\ R & m_D & M \end{matrix}$$

SO(10) GUT

$$\psi_{16} = \begin{pmatrix} u_{iL} & d_{iL} & N_L & e_L \\ u^c_{iL} & d^c_{iL} & N^c_L & e^c_L \end{pmatrix}$$

one generation $\qquad i$ = color

$\psi_{16} \sim \underset{\sim}{16} \qquad \overline{\psi_{16}} \sim \overline{16}$ imaginary

$\qquad\qquad \psi^c_{16} \sim \overline{16}$

$$Y \sim \overline{\psi^c_{16}}\, \psi_{16} \sim \underset{\sim}{16} \times \underset{\sim}{16}$$

$$= \underset{\sim}{10} + \underset{\sim}{120} + \underset{\sim}{126}$$

$$Y = F_{10}\left[\overline{\psi^c_{16}}\, \psi_{16}\right]_{10} \phi_{10} + F_{120}\left[\overline{\psi^c_{16}}\, \psi_{16}\right]_{120} \phi_{120}$$

$$+ F_{126}\left[\overline{\psi^c_{16}}\, \psi_{16}\right]_{126} \phi_{126}$$

This → both Dirac , Majorana mass terms

6 Light Neutrino Model

Add a U(1) for which

ν_R $R = 1$

Scalar Y $R = -1$

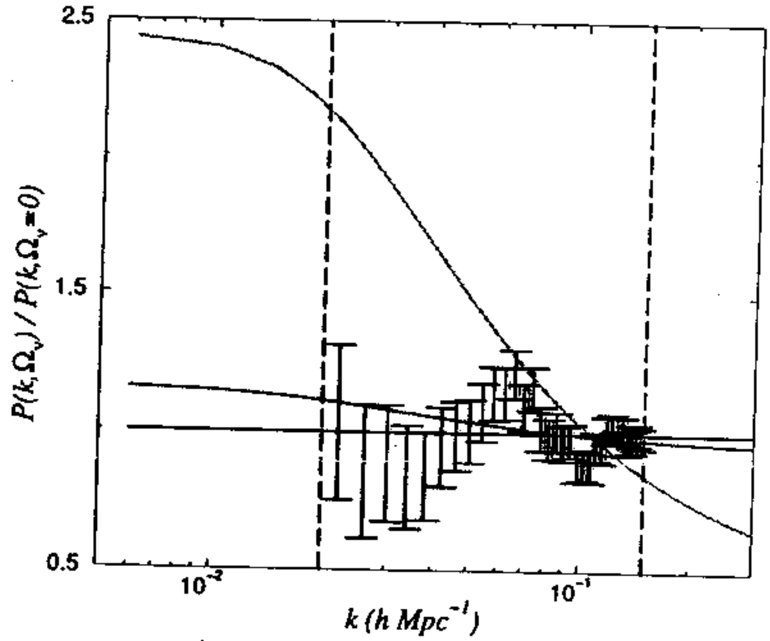
Violate L

$$\nu_L \nu_L \Phi \Phi / M_1 + \nu_R \nu_R Y Y / M_2$$
$$+ \nu_L \nu_R \Phi Y / M_3$$

3 sterile ν mixed in LSND

[redacted]

Elgaroy
astro-ph/0303089
$\Sigma m_\nu < 1$ eV
$m_1 < 1/3$ eV



$\Sigma m_\nu \sim 2.$

Figure 3. Ratio of power spectra for $\Omega_\nu = 0.01$ (bottom line) and $\Omega_\nu = 0.05$ (top li to the one for $\Omega_\nu = 0$ (horizontal line) with amplitudes fitted to the 2dFGRS pow spectrum data (vertical bars) in redshift space. We have fixed $\Omega_m = 0.3$, $h = 0.7$, a $\Omega_b h^2 = 0.02$. The vertical dashed lines limit the range in k used in the fits.

…er spectrum is not affected by redshift …

Astrophysics

1. ν from the Sun

2. Type II Supernovae

   > 99% of energy in
   ν of all types in ~10 sec

   19 $\bar{\nu}_e$ from SN 1987a
   10^{58} were emitted

   ν oscillations can change the spectrum

3. Very high E ν from
   γ ray bursts ? AGN?

Solar Neutrinos

1. Verifying the theory of solar energy

2. Prototypical problem of astrophysics:

So the problem the ν on the Sun

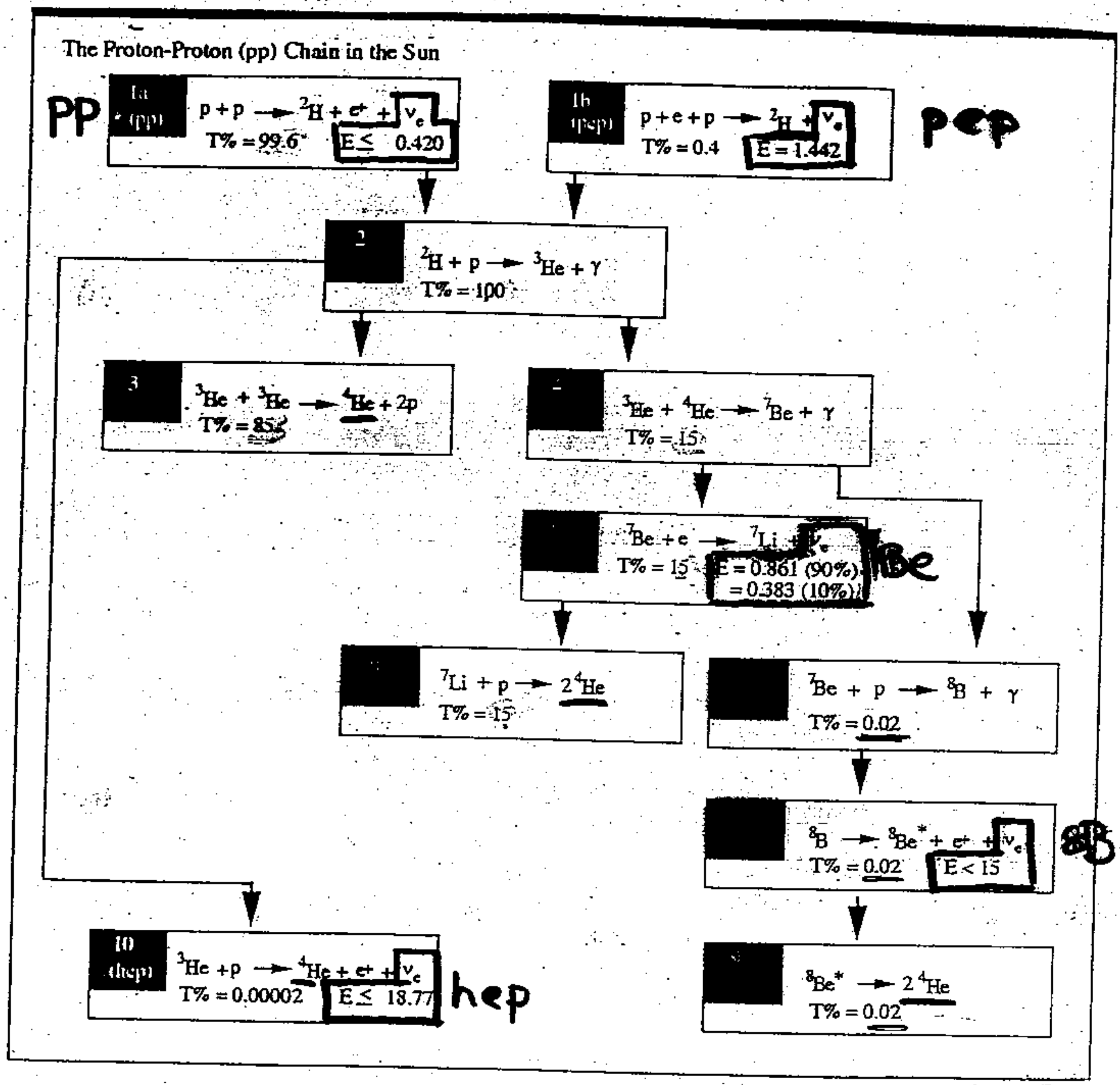
The wonderful solution

SNO (Herb Chen)

$$\frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} \approx \frac{1}{3}$$

Svoboda (DESK COPY) (please remove only ... copy

Solar Energy Production



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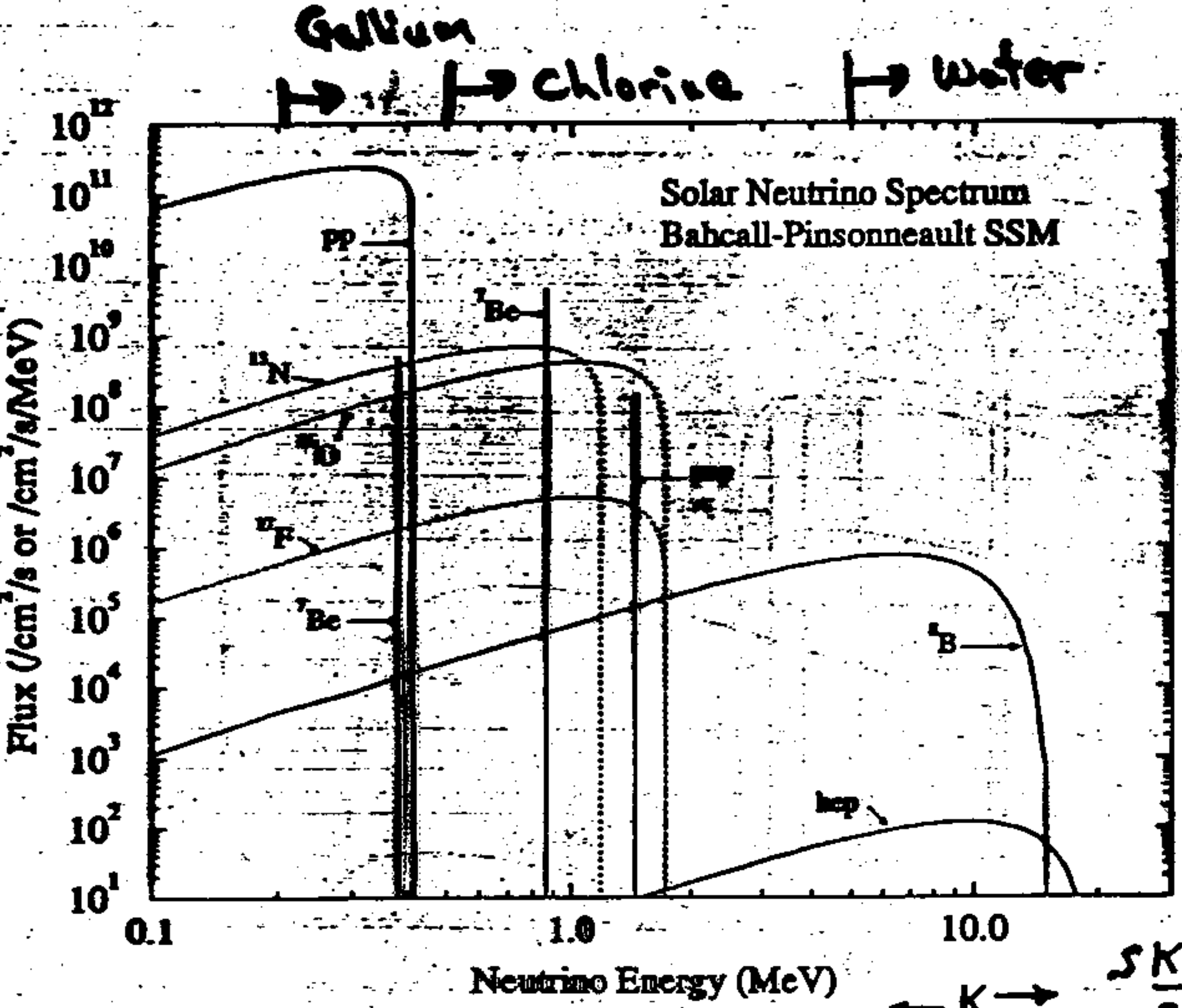
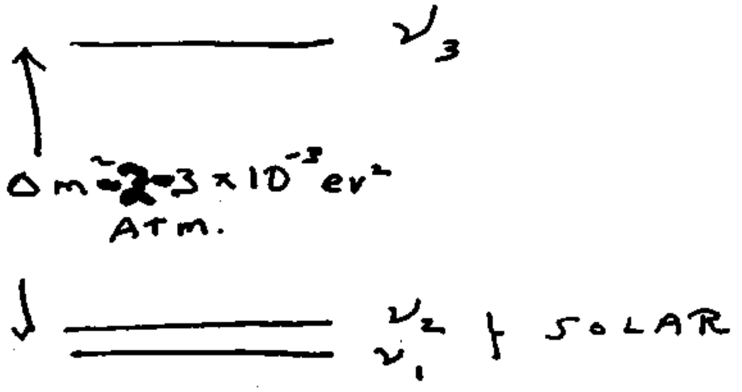


← K → $\frac{SKAM}{SSM} = .47 \pm .02$

← DAVIS → $\frac{DAVIS}{SSM} = .33 \pm .0$

← GALLIUM — $\frac{GA}{SSM} = .56 \pm .0$



LMA-MSW
$\theta_\odot \sim$ [illegible]
$\Delta m^2_{12} \sim$ [illegible] eV^2

$$\nu_3 \approx (\nu_\mu + \nu_\tau)/\sqrt{2} + s_{13}\nu_e$$

$$\nu_2 = \sin\theta_\odot\, \nu_e + \cos\theta_\odot\, (\nu_\mu - \nu_\tau)/\sqrt{2}$$

$$\nu_1 = -\cos\theta_\odot\, \nu_e + \sin\theta_\odot\, (\nu_\mu - \nu_\tau)/\sqrt{2}$$

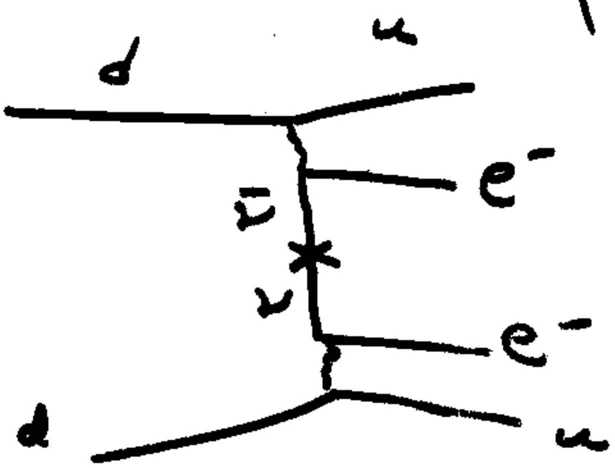
MAJOR QUESTIONS

1. $s_{13} = |s_{13}| e^{i\delta}$ What is $|s_{13}|, \delta$?
2. Inverse hierarchy?
3. Solar solution: $\Delta m^2_{12}, \theta_\odot$
4. Non standard: $\nu_{sterile}$, FCNC, ..
5. What is m_1?
6. Majorana or Dirac?
7. 2 Majorana phases?

Possible signal for a Majorana ν

is Neutrinoless Double β-Deca

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



$^{76}Ge \to {}^{76}Se$

"$m(\nu_e)$" $\lesssim 0.5\,eV$ from ^{76}Ge

depends on nuclear calculations

really "$m(\nu_e)$" $= \sum_\alpha \eta_\alpha |U_{e\alpha}|^2 m$

$= M$

η_2 and $\eta_3 = \pm 1$

are CP eigenvalues of Majorana ν

or $\eta_2 = e^{i\beta}$ $\eta_3 = e^{i\alpha}$

CP Violation in ν Oscillation

(Detecting the phase δ)

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

1. Rate is proportional to S_{13}^2
2. Difference depends not only on Δm^2_{32}, but also $\underline{\Delta m^2_{21}}$

   Requires long baseline and/or low
3. In matter the difference is <u>not</u> a direct sign of ~~CP~~.

   Fit data to S_{13} and δ and hierarchy
4. T violation ("no" matter effect)

   Cf $\nu_\mu \rightarrow \nu_e$ with $\nu_e \rightarrow \nu_\mu$

Neutrinos
(Steering Committee, APS Study)

1. Solar neutrinos
   a. $^7Be\ \nu$ - Borexino
   b. $pp\ \nu$ - R+D

2. Double beta decay

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

76 Ge, ^{136}Xe, ^{130}Te ...,
... Mo

3. Mixing matrix

$$\begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & \theta_{13} e^{i\delta} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Detect θ_{13} - (1) Reactor
(2) Off-axis Fermilab - NOvA
(3) JPARK to SK

Are there questions with no answers?

1. Why this set of characters
   $e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$
   u, d, c, s, t, b
2. Why baryons (not anti-b
   Ω_b

Lessons from Kepler:

1. Why only 6 planets?

Past 20 Years

I Neutrino Astronomy

1. Solar neutrinos
2. Supernova 1987a

II. Particle Physics

1. Neutrino mass – the first signal of physics beyond the standard model
2. Neutrino mass is the first component of dark matter identified

Next 20 Years

I Neutrino Astronomy

1. Complete solar neutrino detection
   Be and pp neutrinos
2. Supernova watch
3. Extra-galactic neutrino search

II Particle Physics

1. Dirac or Majorana
2. S_{13} and CP Violation
3. Sterile neutrinos?