National Nuclear Physics Summer School

Neutrino Physics
Lecture I
July 16, 2007

Stuart Freedman
Berkeley

Goals of these lectures:

- Survey the important discoveries about neutrinos.
- Discuss the key experimental techniques.
- Discuss the important theoretical concepts.

We will avoid theoretical details. I assume some background and general familiarity with the relevant framework: relativistic kinematics, quantum mechanics and relativistic quantum mechanics, basic ideas of quantum field theory… Boris Kayser will lecture on current and future theoretical directions.

We will survey experiments assuming a basic understanding of common experimental techniques: energy loss of charged particles, basic spectrometry and other common experimental techniques…

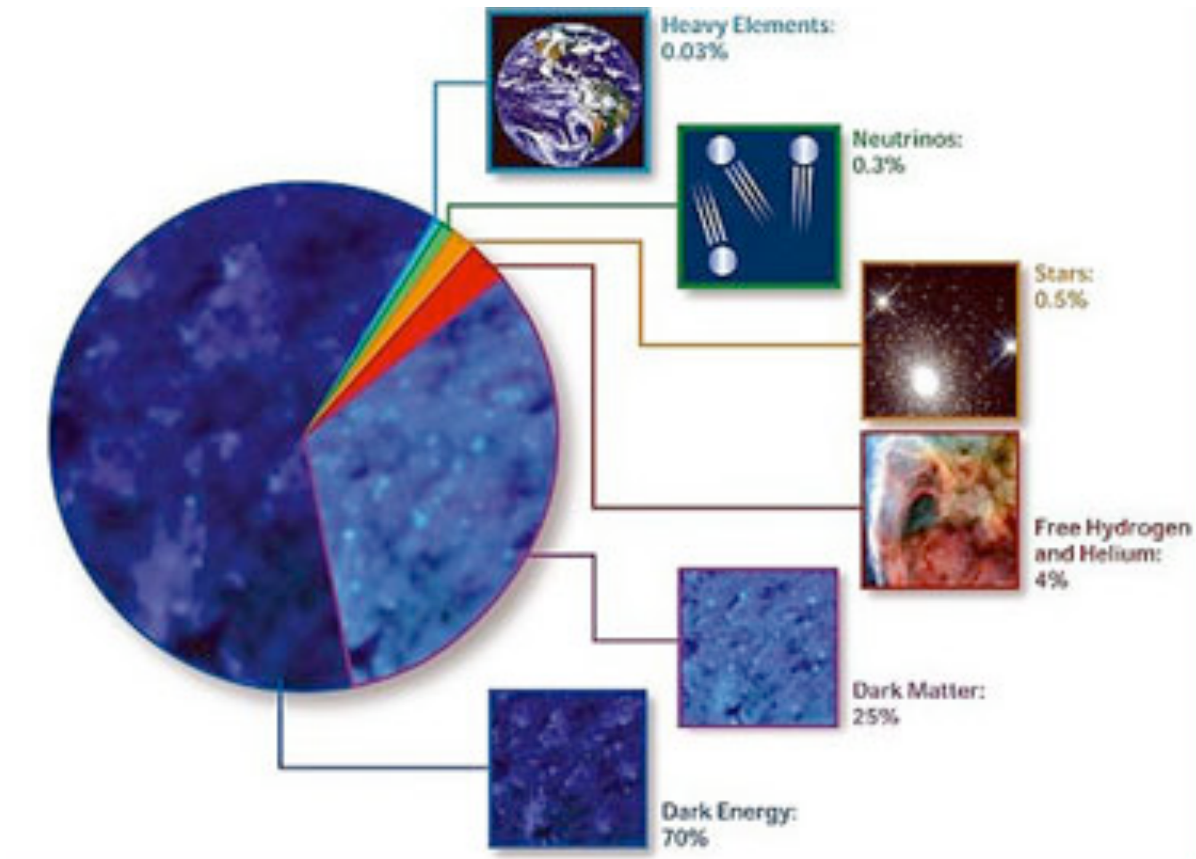
We will take a historical approach when it provides useful insights or interesting stories.

Top 10 reasons to believe that neutrinos have mass

10. Neutrinos are the missing mass of the universe.

6. Most theorists now believe that neutrinos have mass.

No!



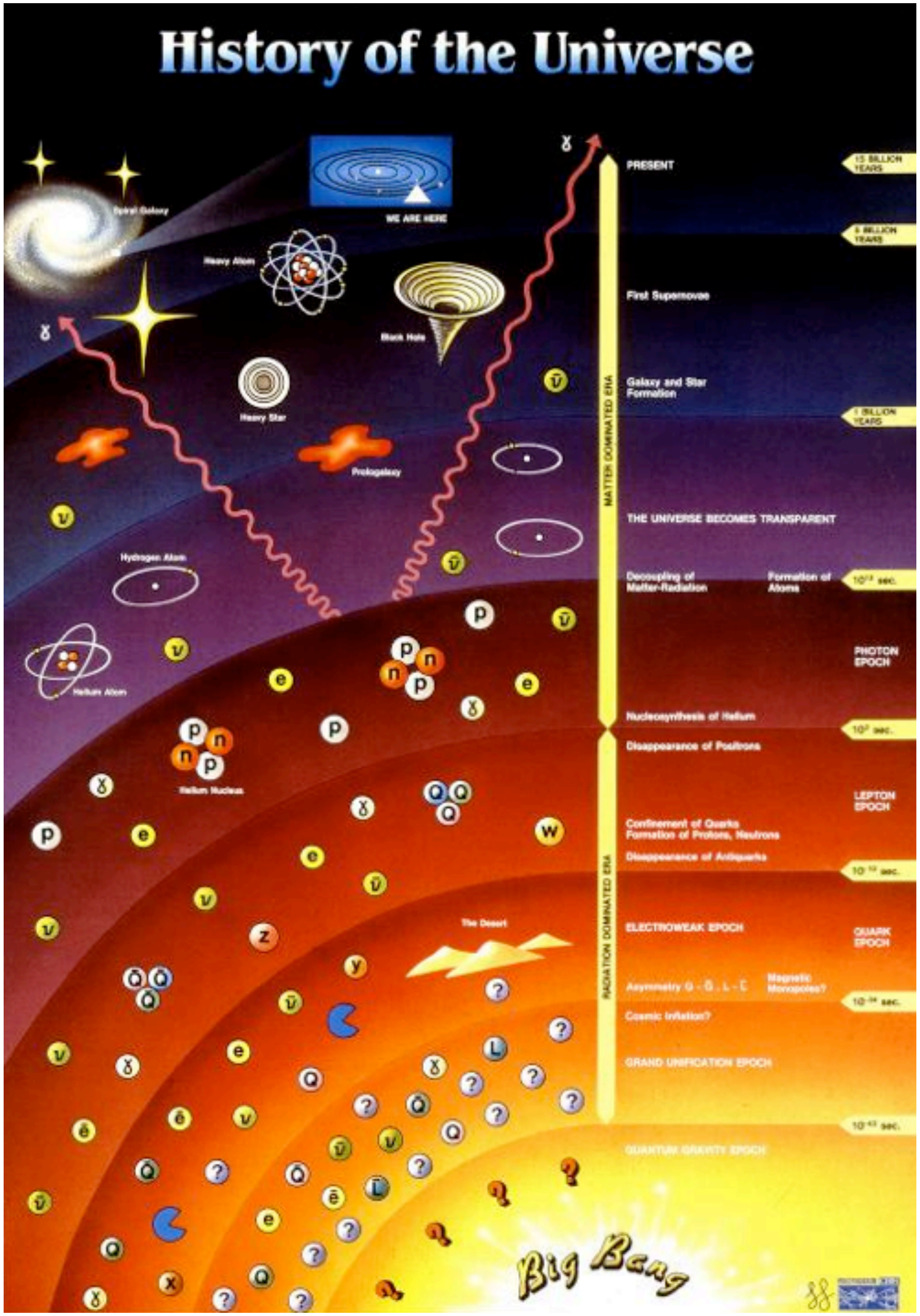
Top 10 reasons to believe that neutrinos have mass

4. Experiments show neutrinos have mass.

3. There is no known symmetry principle that forbids neutrino mass.

1. Neutrinos "naturally" in Grand Unified Theories have mass!

$$\begin{bmatrix} q^+ \\ q^- \end{bmatrix} \quad \begin{bmatrix} l \\ \nu \end{bmatrix} \qquad\qquad \begin{bmatrix} q^+ \\ q^- \\ l \\ \nu \end{bmatrix}$$



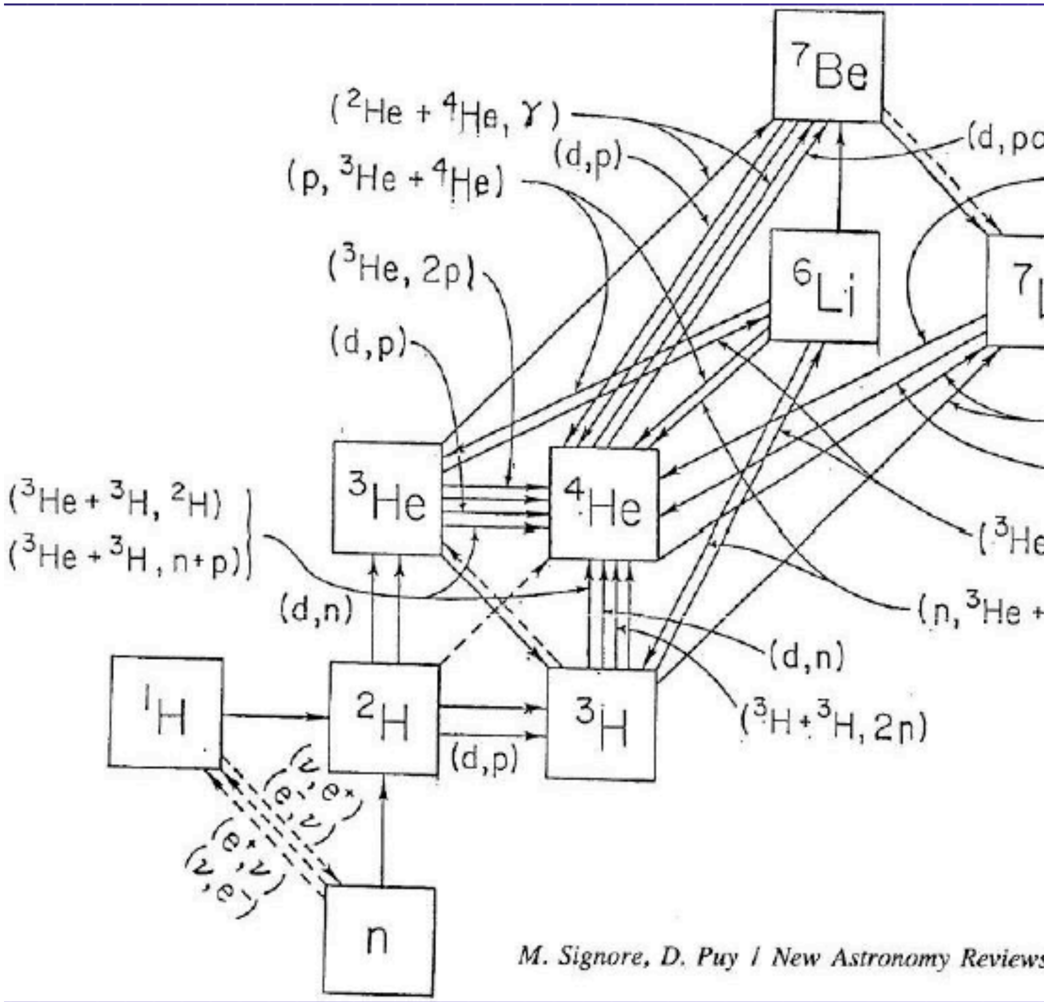
Neutrinos

• Created in equal abundance to other particles in the Big Bang.

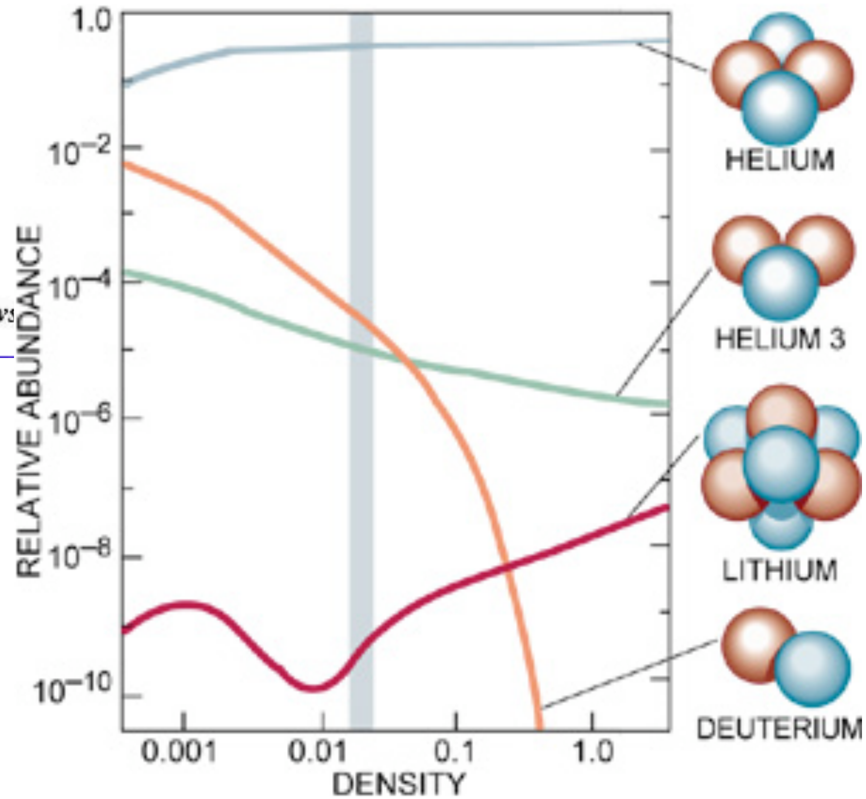
• About 300/cm^3 left over from the Big Bang.

• T ~ 1.9K° primordial background radiation .

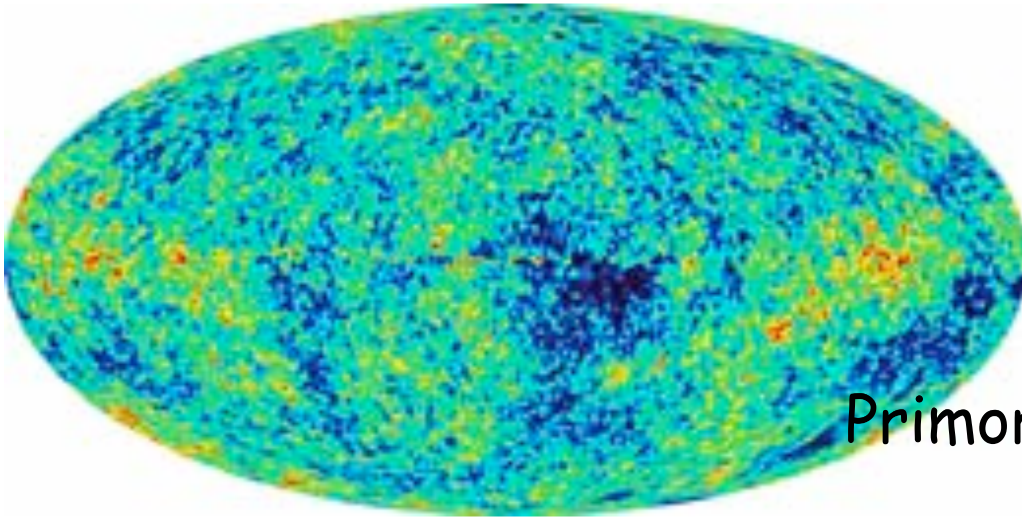
• Light relativistic particles were critical in determining the cooling rate of the universe.



M. Signore, D. Puy / New Astronomy Reviews



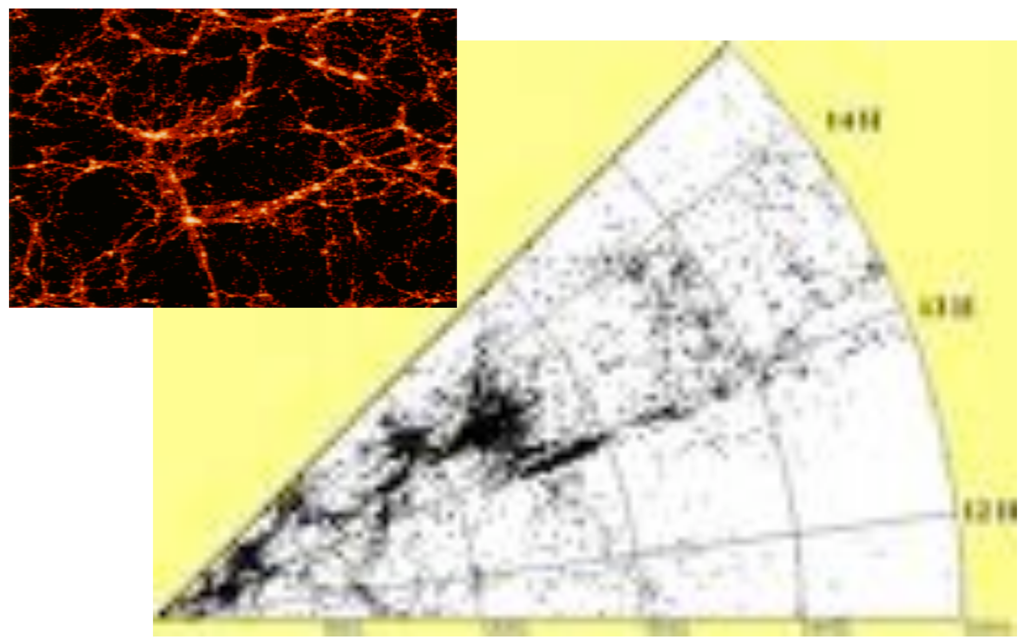
Cosmological connection to neutrinos



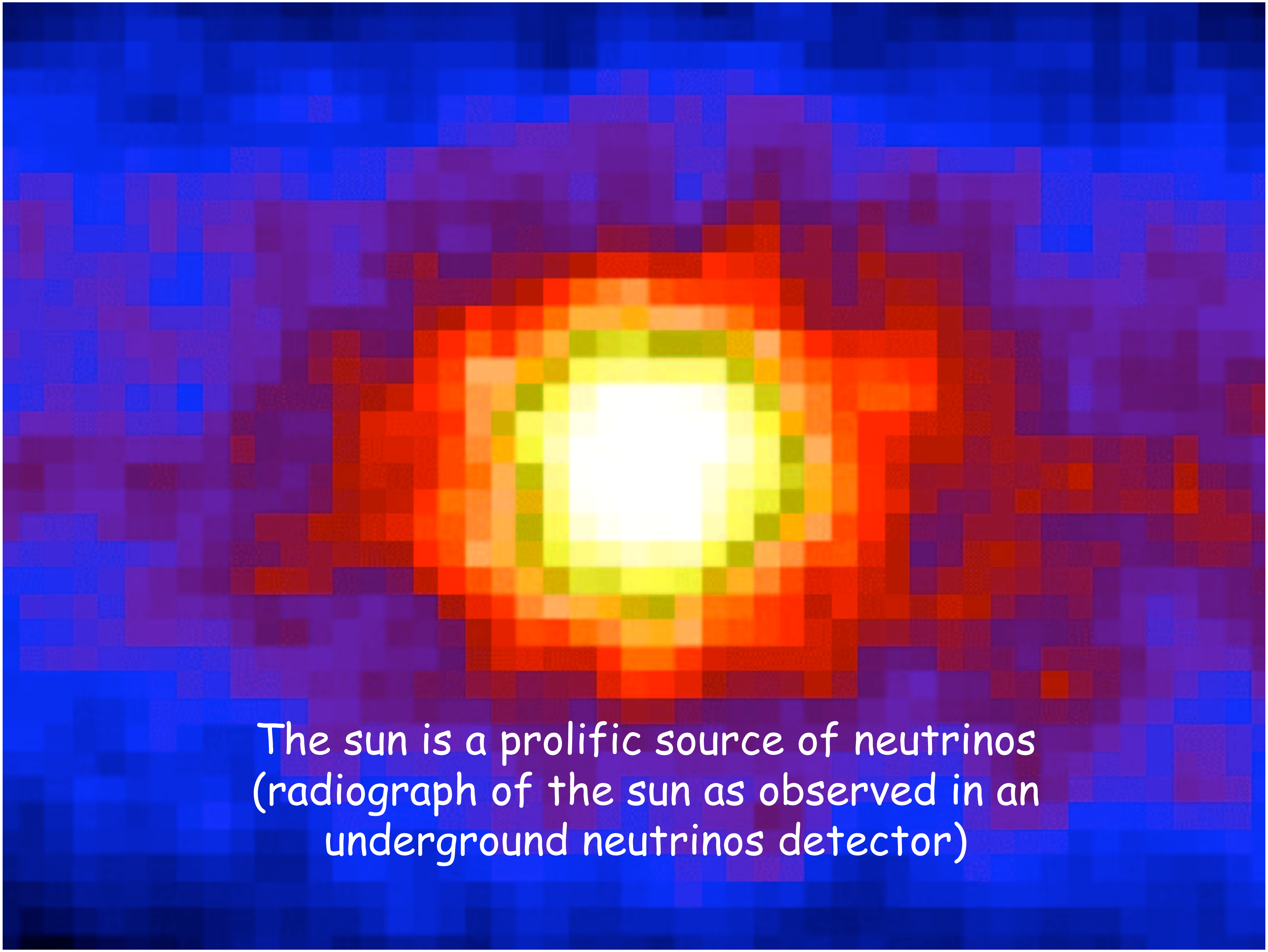
Primordial microwave background

$$\sum_i m_i$$

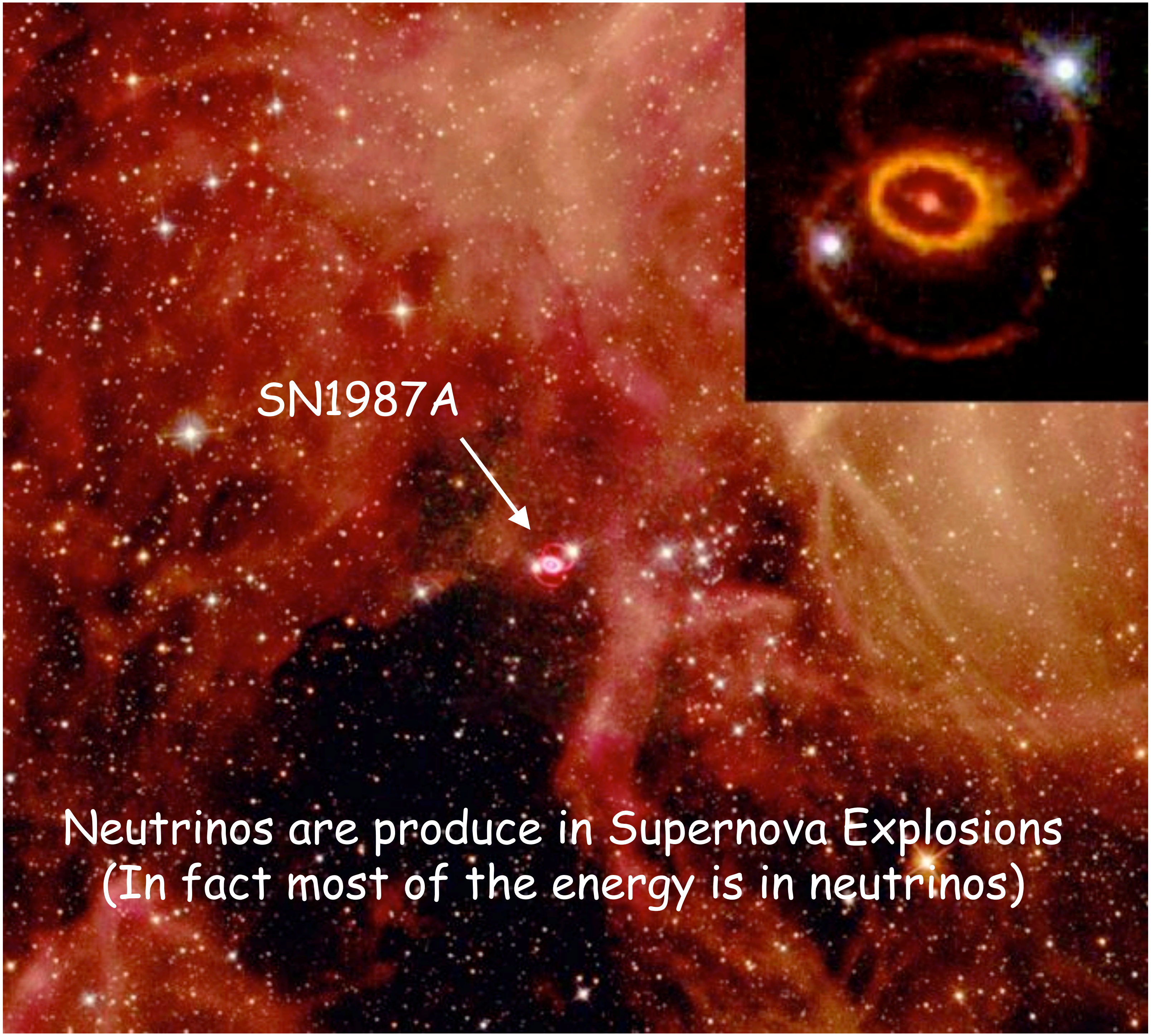
Neutrino mass



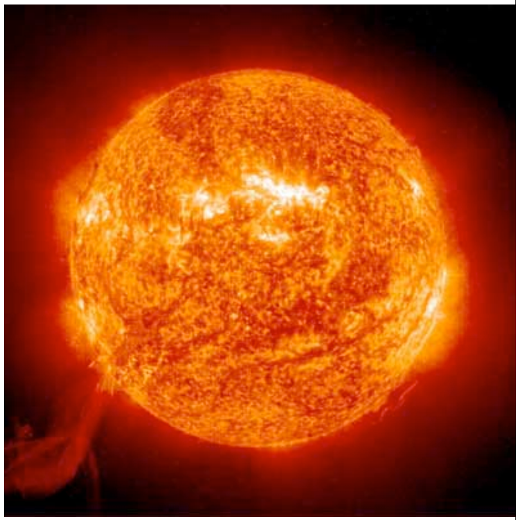
Large scale structure



The sun is a prolific source of neutrinos (radiograph of the sun as observed in an underground neutrinos detector)


SN1987A
Neutrinos are produce in Supernova Explosions
(In fact most of the energy is in neutrinos)

Neutrino Energies

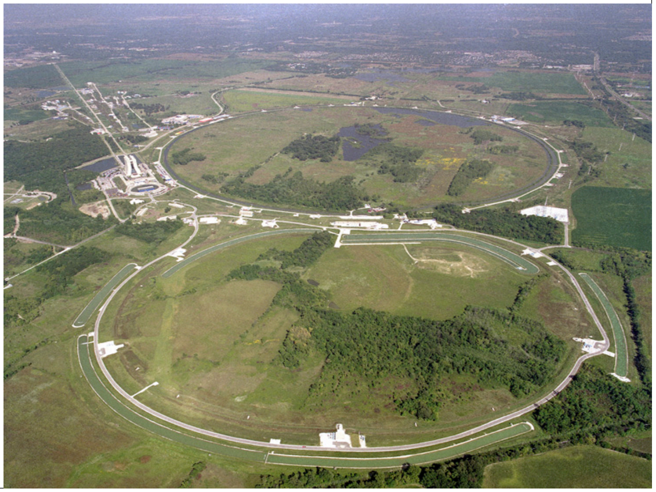


Big-Bang neutrinos ~ 0.0004 eV

Neutrinos from the Sun < 20 MeV

Atmospheric neutrinos ~ GeV

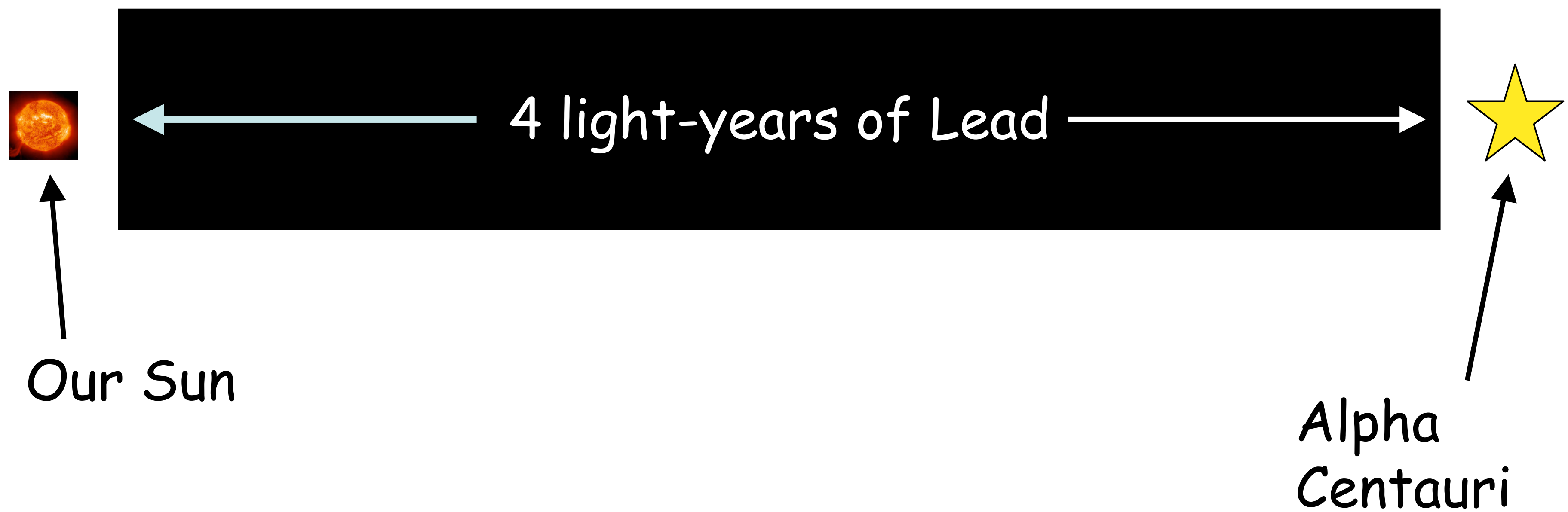
Antineutrinos from nuclear reactors < 10.0 MeV

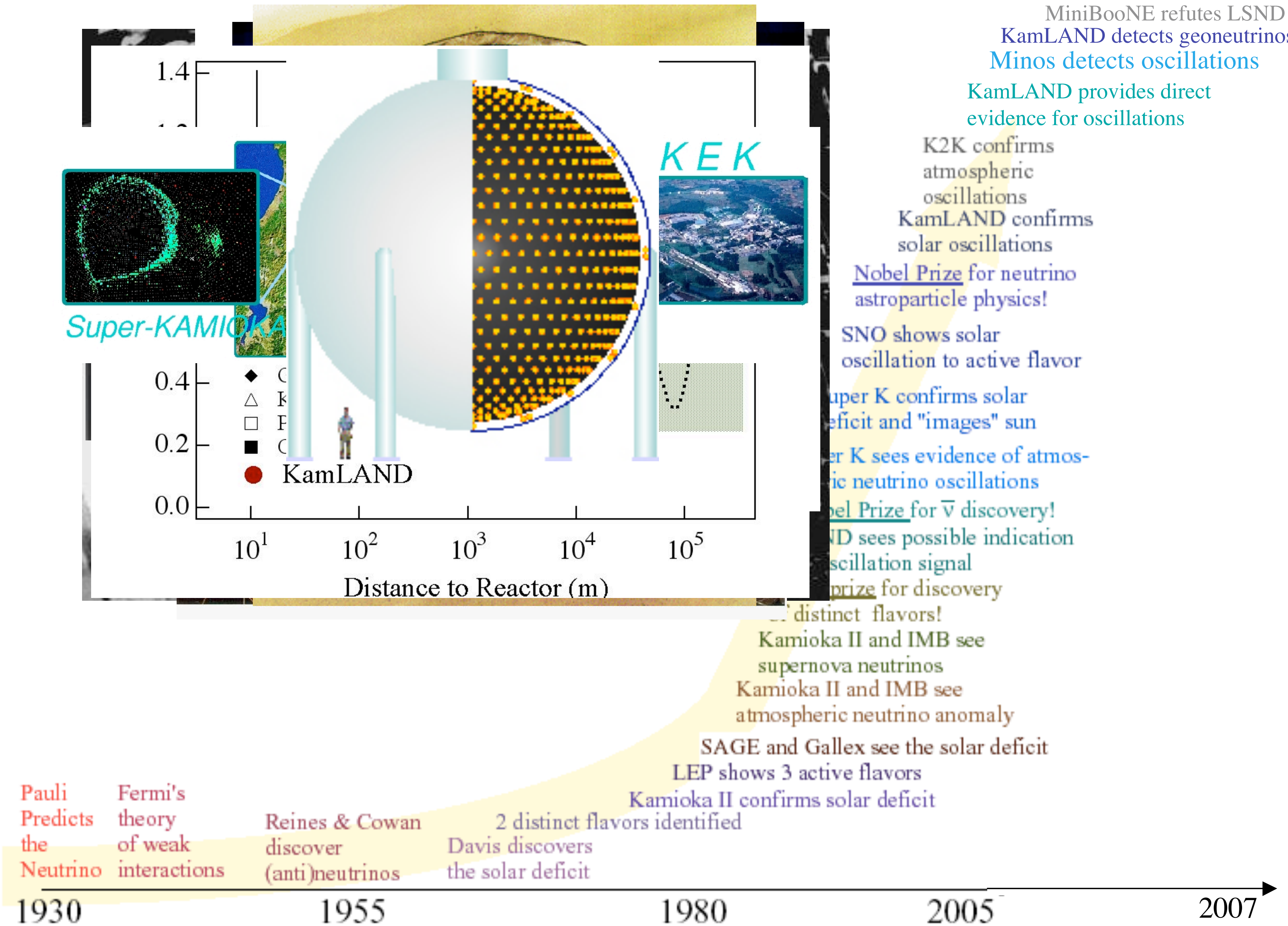


Neutrinos from accelerators up to GeV (10^9 eV)

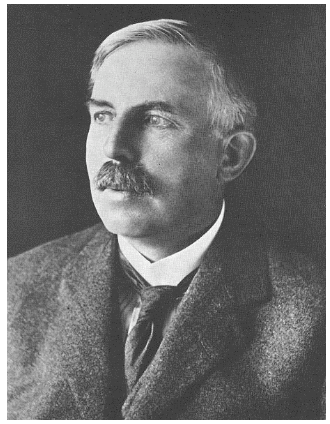
Neutrinos are <u>very</u> weakly interacting

Four light-years of lead would not appreciably shield us from the neutrinos from the closest star!




MiniBooNE refutes LSND
KamLAND detects geoneutrinos
Minos detects oscillations
KamLAND provides direct evidence for oscillations
K2K confirms atmospheric oscillations
KamLAND confirms solar oscillations
Nobel Prize for neutrino astroparticle physics!
SNO shows solar oscillation to active flavor
uper K confirms solar eficit and "images" sun
er K sees evidence of atmos- ic neutrino oscillations
bel Prize for $\bar{\nu}$ discovery!
ID sees possible indication scillation signal
prize for discovery distinct flavors!
Kamioka II and IMB see supernova neutrinos
Kamioka II and IMB see atmospheric neutrino anomaly
SAGE and Gallex see the solar deficit
LEP shows 3 active flavors
Kamioka II confirms solar deficit
2 distinct flavors identified
Davis discovers the solar deficit
Reines & Cowan discover (anti)neutrinos
Fermi's theory of weak interactions
Pauli Predicts the Neutrino
1930
1955
1980
2005
2007
Super-KAMIOKA
KEK
1.4
0.4
0.2
0.0
KamLAND
10^1 10^2 10^3 10^4 10^5
Distance to Reactor (m)

Becquerel



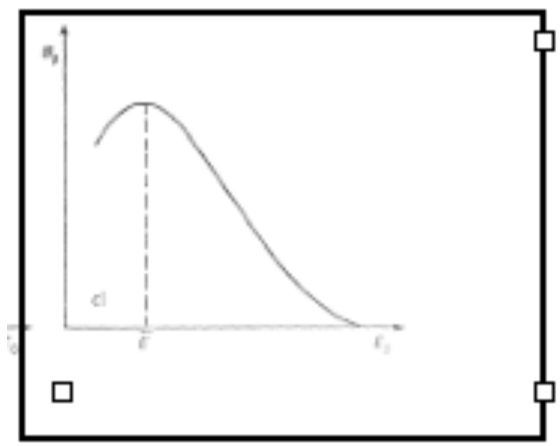
Rutherford

Meitner

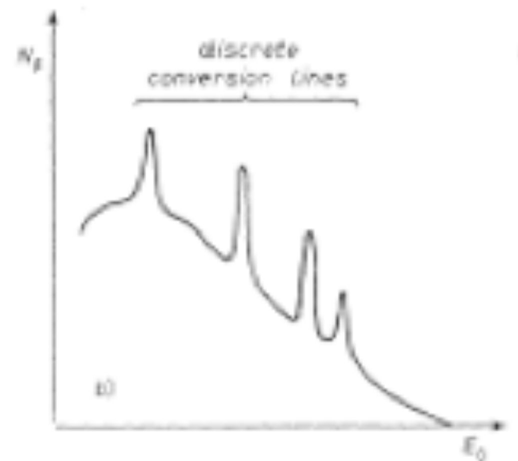
Chadwick

$$N_P \rightarrow N_D + e^-$$

$$E_e \approx (M_P - M_D) - m_e$$



Continuous Spectrum?



Complications from internal conversion

The existence of the neutrino

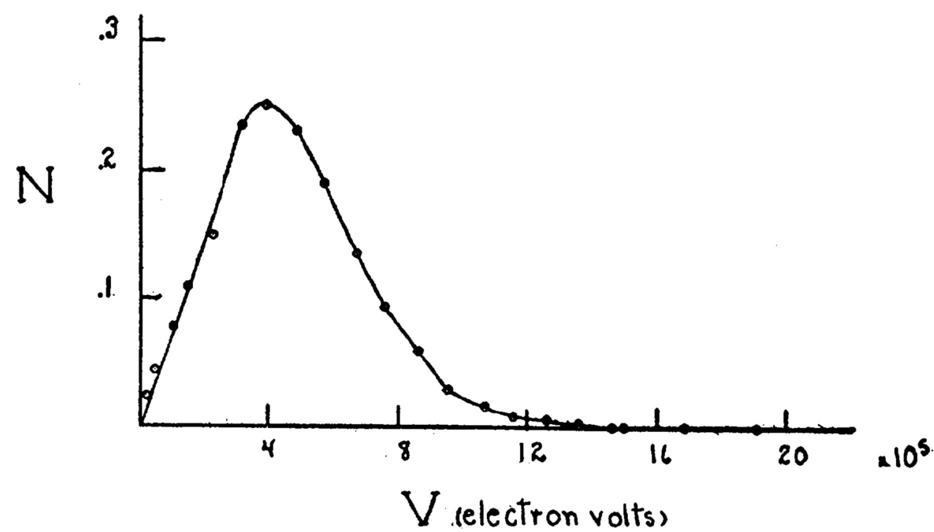
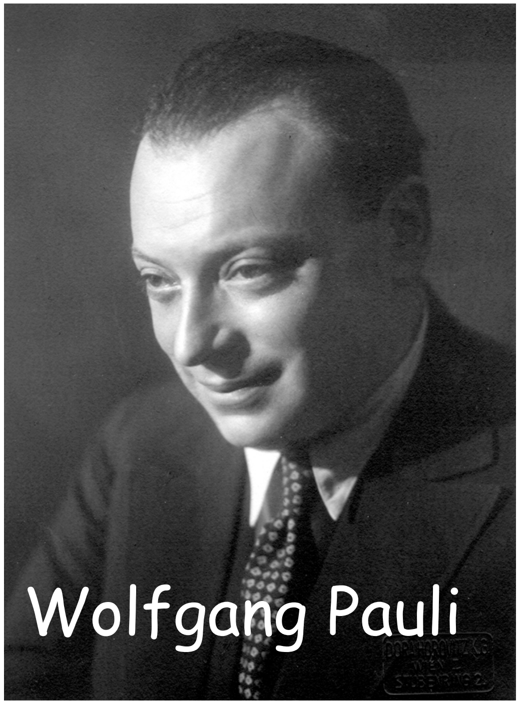


FIG. 5. Energy distribution curve of the beta-rays.

Bohr: *At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations.*



First "letter" on "neutrinos"

(Never published, often cited)

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

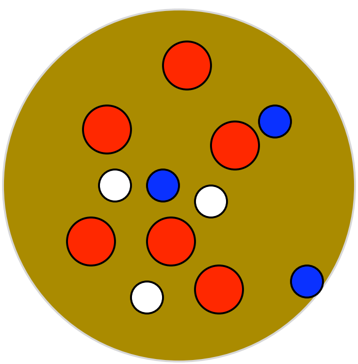
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.



^{6}Li

$$^{6}He \Rightarrow {}^{6}Li + e^{-} + \overline{\nu}$$

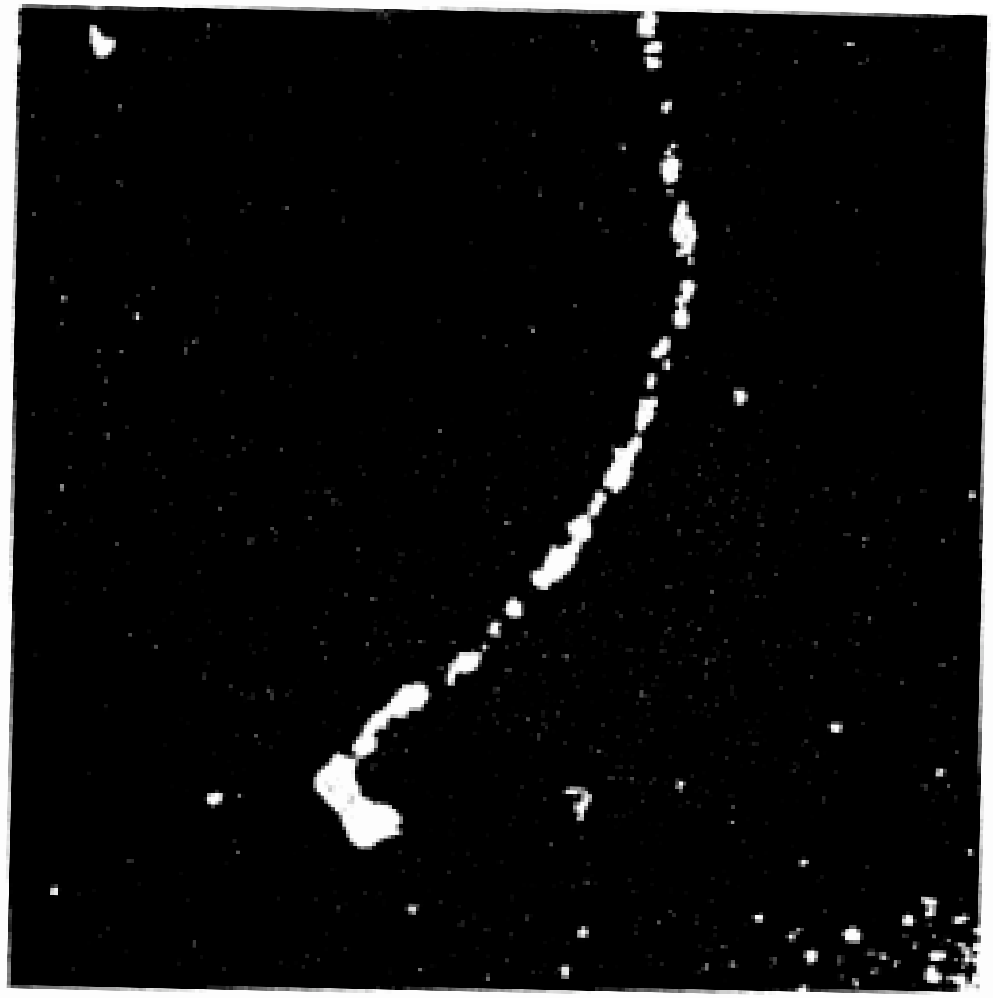


Fig. 1.2. Cloud chamber picture of the decay of He^6 (CSIKAI *et al.* [1958]).

Fermi's Theory of the Weak Interaction

ANNO IV - VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

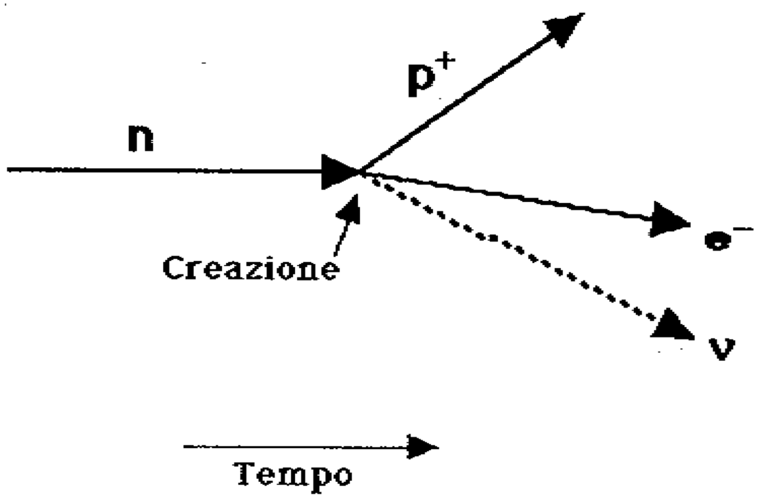
LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL' ECONOMIA NAZIONALE

Tentativo di una teoria dell' emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.



Fermi's notes on QM

Important special case, at $t=0$ system in state n. Then $a_n(0)=1$, all other a's are zero.

$$(10)\quad a_s(t) = -\frac{i}{\hbar}\int_0^t \mathcal{H}_{sn}(t)\, e^{\frac{i}{\hbar}(E_0^{(s)}-E_0^{(n)})t}\,dt \qquad (s\neq n)$$

Matrix element $\mathcal{H}_{sn}(t)$ causes transitions $n \to s$.

Transitions from n to a continuum of states

Assume $\mathcal{H}_{sn}$ indep. of time, then

$$(11)\quad a_s(t) = -\mathcal{H}_{sn}\frac{e^{\frac{i}{\hbar}(E_0^s-E_0^n)t}-1}{E_0^s-E_0^n}$$

$$|a_s(t)|^2 = 4|\mathcal{H}_{sn}|^2 \frac{\sin^2\frac{t}{2\hbar}(E_0^{(s)}-E_0^{(n)})}{(E_0^{(s)}-E_0^{(n)})^2}$$

Prob of transition to one state s

$$(12)\quad P(t) = \sum_s |a_s(t)|^2 = 4\overline{|\mathcal{H}_{sn}|^2}\sum \frac{\sin^2\frac{t}{2\hbar}(E^s-E^n)}{(E^s-E^n)^2} =$$

$$= 4\overline{|\mathcal{H}_{sn}|^2}\rho(E_n)\underbrace{\int\frac{\sin^2\frac{t}{2\hbar}(E^s-E^n)\;d(E^s-E^n)}{(E^s-E^n)^2}}_{\frac{\pi t}{2\hbar}}$$

$$= t\,\frac{2\pi}{\hbar}\overline{|\mathcal{H}_{sn}|^2}\rho(E_n)$$

$$\int\frac{\sin^2 \alpha x}{x^2}dx = \frac{\pi}{2}$$

(13) $\rho(E_n)$ = no of states s, close to E_n per unit energy interval.

$$\boxed{\text{Rate of transition} = \frac{2\pi}{\hbar}\overline{|\mathcal{H}_{sn}|^2}\rho(E_n)}$$

Discuss: distribution of final states as function of t & relation with uncertainty principle

Fermi's "Golden Rule #2"

Shape factor in allowed beta decay

$$\frac{dN}{dt\,dE_0} = \frac{2\pi}{\hbar} \mid M^2 \mid \rho(E_0)$$

$$dn = \frac{V\,4\pi p^2 dp}{\hbar^3} = \frac{V\,4\pi pE dE}{\hbar^3}$$

$$\rho(E_0) = \frac{dn_e}{dE}\frac{dn_\nu}{dE_\nu} = \frac{p_e E p_\nu E_\nu V^2}{4\pi^2\hbar^6}$$

$$\rho(E_0) = \frac{\sqrt{E^2 - m_e^2}\,E\sqrt{(E_0 - E)^2 - m_{\nu_e}^2}\,(E_0 - E)V^2}{4\pi^2\hbar^6}$$

$$E_0 = E + E_\nu$$

hundertmal kleiner sind als die der erlaubten Übergängen.

7. Die Masse des Neutrinos. Durch die Uebergangswahrscheinlichkeit (32) ist die Form des kontinuierlichen β-Spektrum bestimmt. Wir wollen zuerst diskutieren, wie diese Form von der Ruhmasse μ des Neutrinos abhängt, um von einem Vergleich mit den empyrischen Kurven diese Konstante zu bestimmen. Die Masse μ ist in dem Faktor p_0^2/v_0 enthalten. Die Abhängigkeit der Form der Energieverteilungskurve von μ ist am ausgeprägtesten in der Nähe des Endpunkts der Verteilungskurve. Ist E_0 die Grenzenergie der β-Strahlen, so sieht man ohne Schwierigkeit dass die Verteilungskurve der β-Strahl Energie für Energien E in der Nähe von E_0 proportional ist zu

$$\frac{p_0^2}{v_0} = \frac{1}{c^3}\left(\mu c^2 + E_0 - E\right) \cdot \sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)} \qquad (36)$$

$$\frac{p_0^2}{v_0} = \frac{1}{c^3}\left(\mu c^2 + E_0 - E\right) \sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}. \qquad (36)$$

Nella fig. 1 la fine della curva di distribuzione è rappresentata per $\mu = 0$, e per un valore piccolo e uno grande di μ. La maggiore somiglianza con le

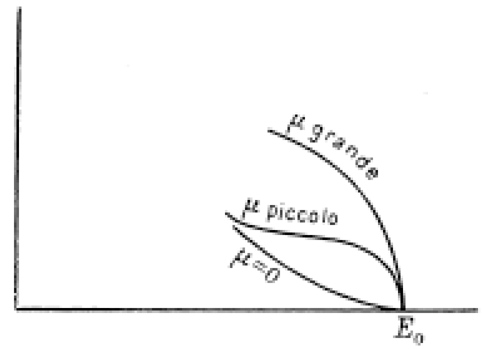
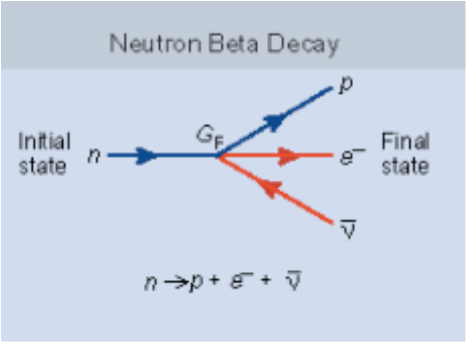
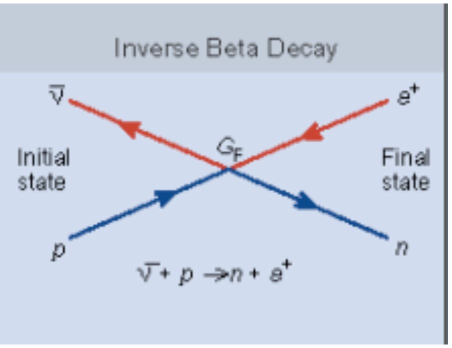


Fig. 1.

curve sperimentali si ha per la curva teorica corrispondente a $\mu = 0$. Arriviamo così a concludere che la massa del neutrino è uguale a zero o, in ogni caso, piccola in confronto della massa dell'elettrone [8]. Nei calcoli che seguono porremo per semplicità $\mu = 0$.

Fermi's Theory suggests "detectable" neutrinos





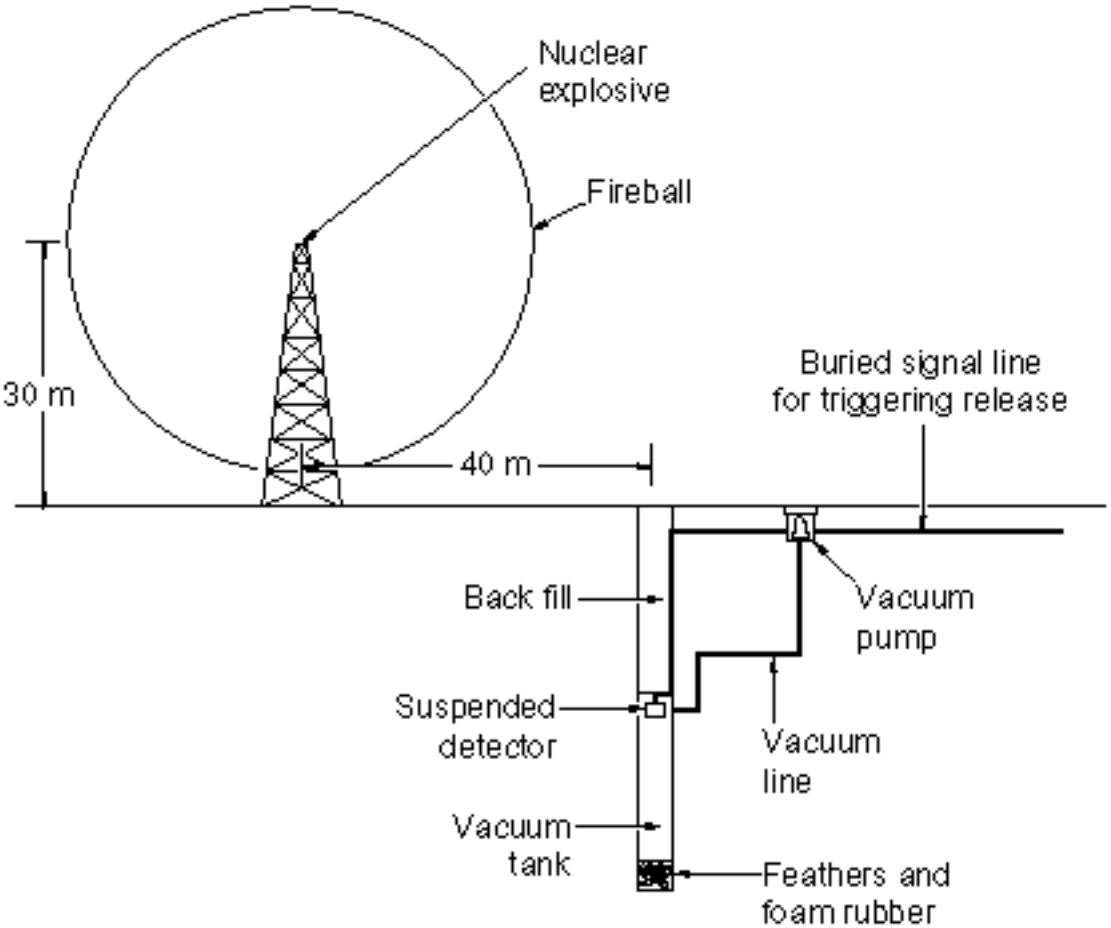
$$\sigma_{\text{tot}}^{(0)} = \sigma_0 (f^2 + 3g^2) E_e^{(0)} p_e^{(0)}$$

$$= 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1\ \text{MeV}^2} \right) \times 10^{-42}\ \text{cm}^2$$

$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C}{\pi} (1 + \Delta_{inner}^R)$$

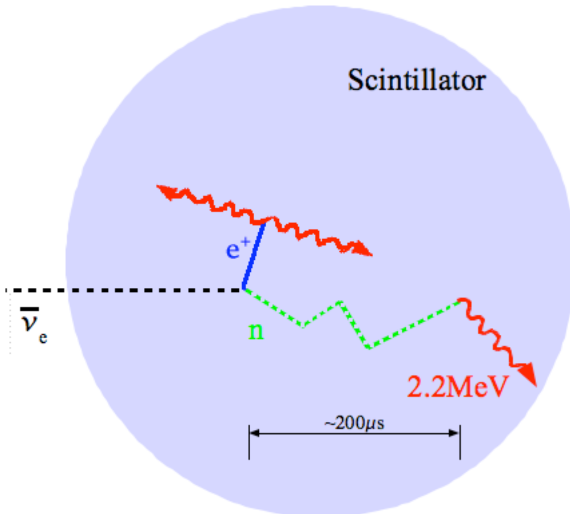
$$\sigma_{\text{tot}}^{(0)} = \frac{2\pi^2 / m_e^5}{f_{p.s.}^R \tau_n} E_e^{(0)} p_e^{(0)}$$

First proposal for direct detection of the neutrino



Hanford Pile

First Direct Detection of the Neutrino

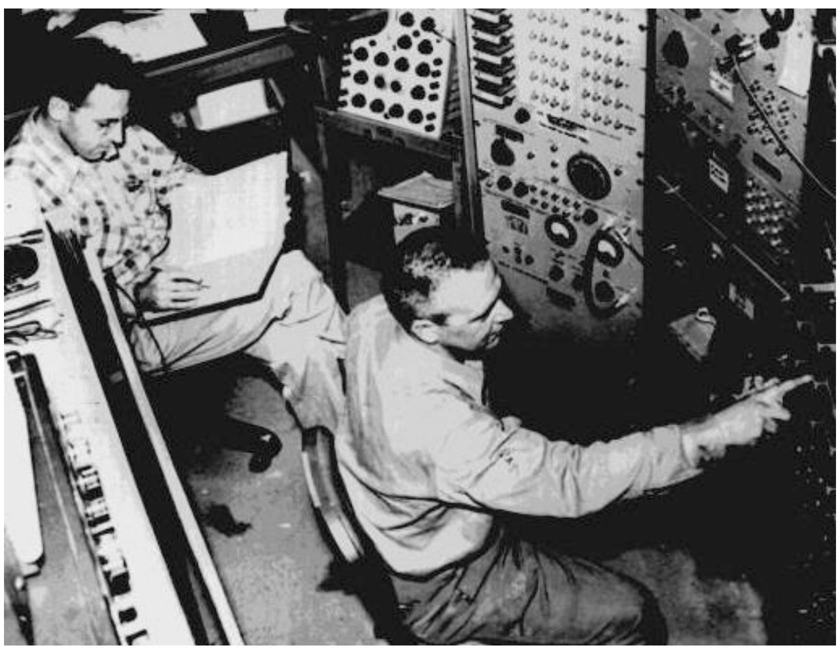


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

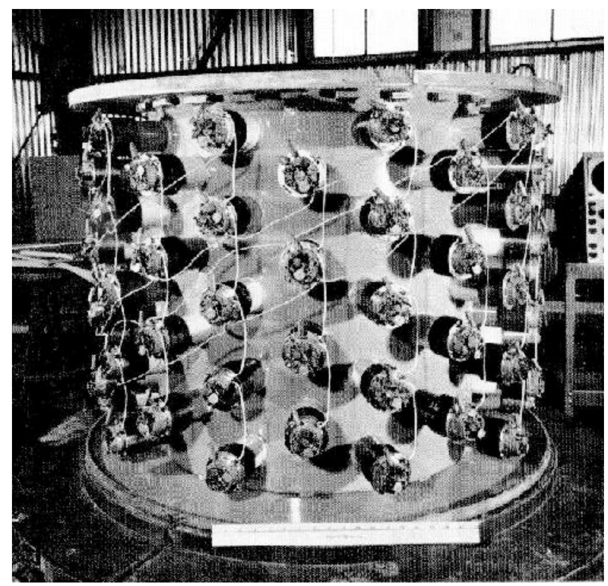
$$\tau \approx 200\ \mu s$$

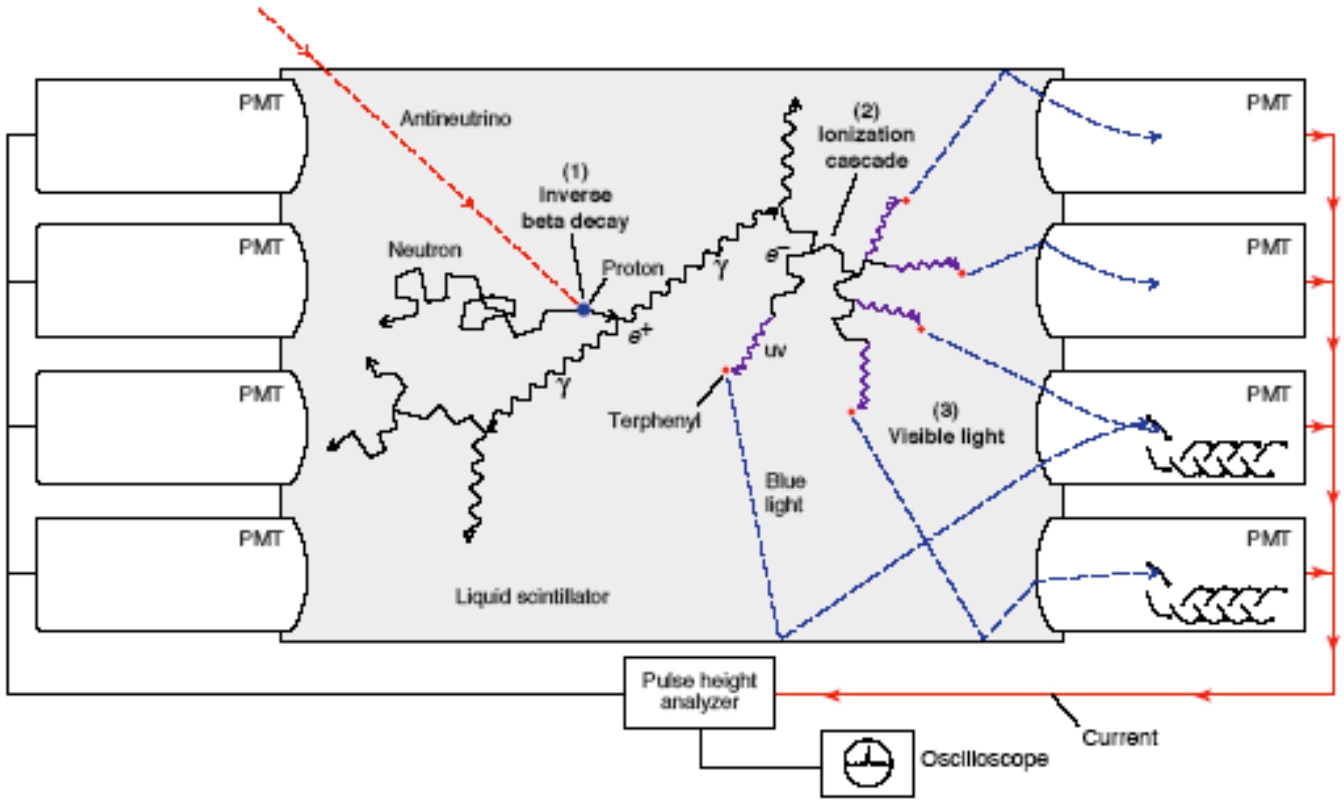
$$n + p \rightarrow d + \gamma\,(2.2\ MeV)$$

$$E_{prompt} \cong E_\nu - \overline{E}_n - 0.8\ MeV$$

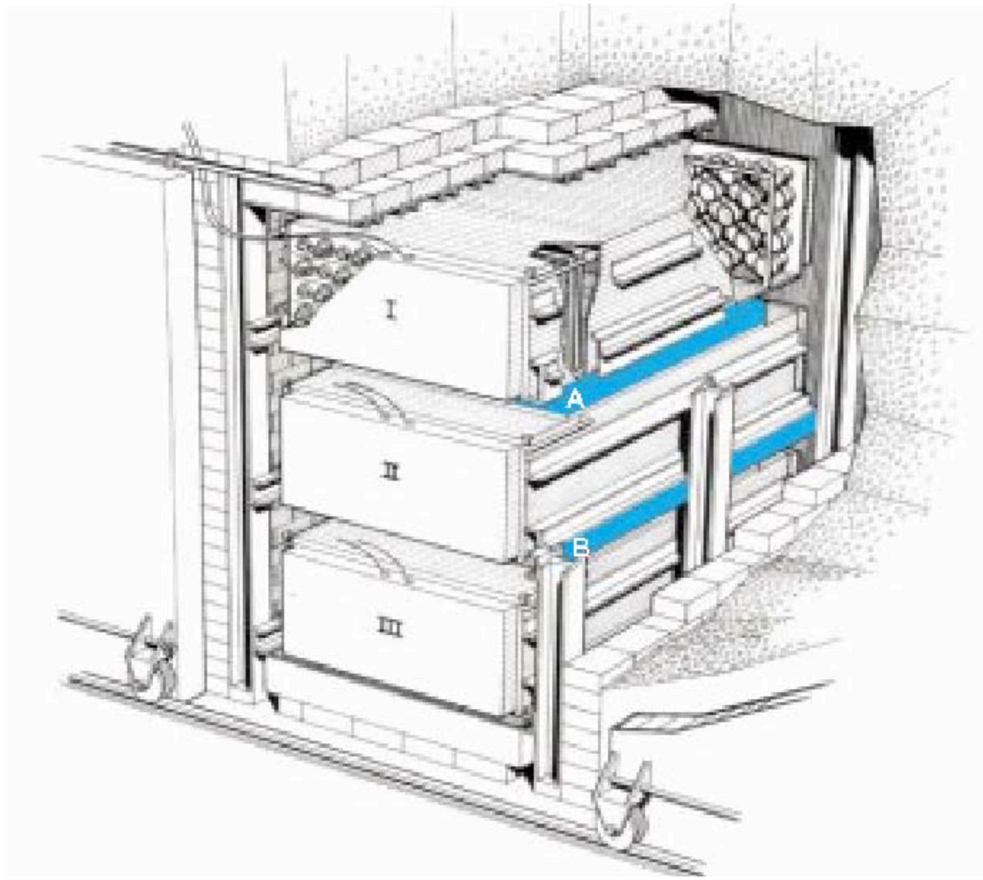


Reines and Cowan 1956

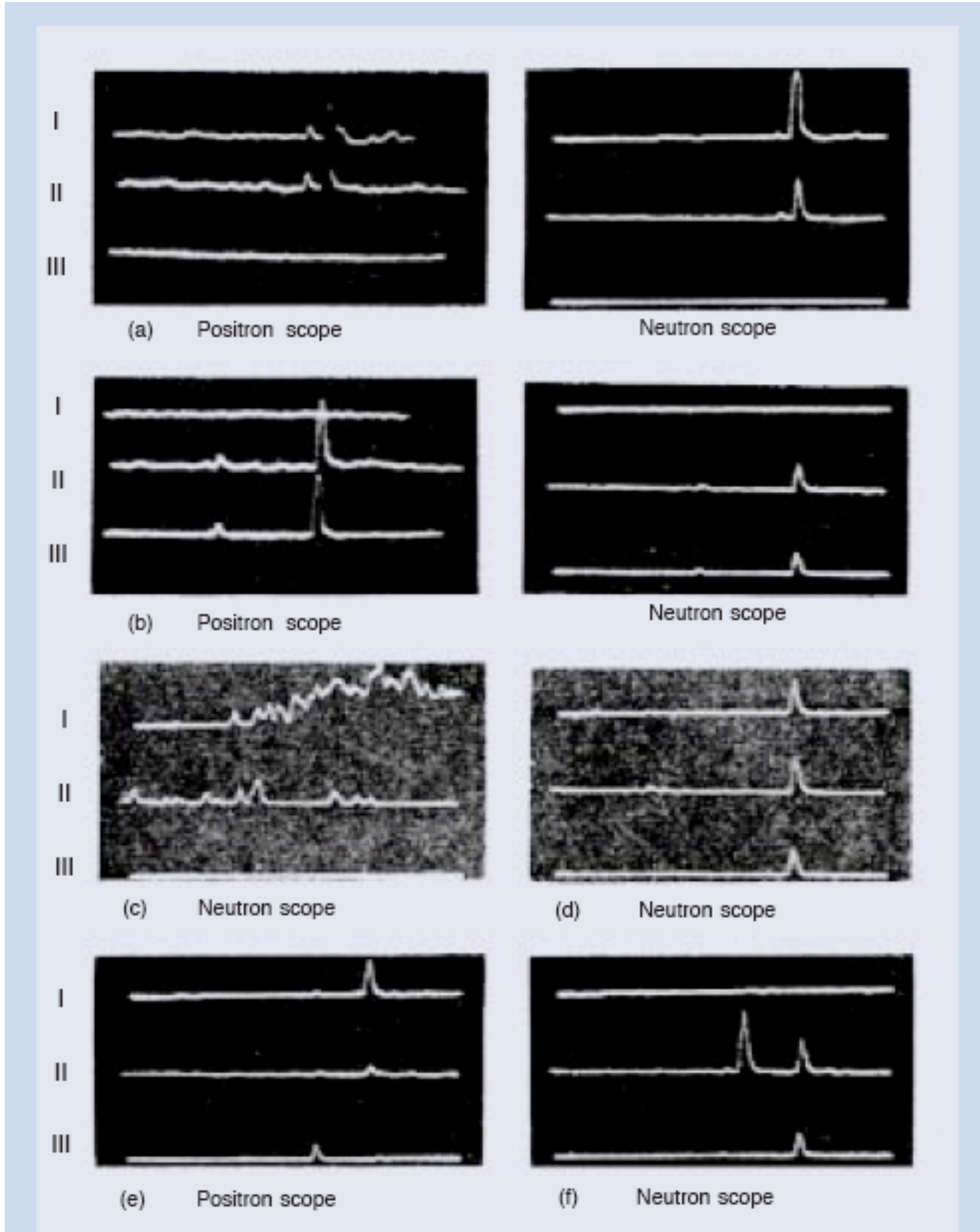




PMT
PMT
PMT
PMT
PMT
PMT
PMT
PMT
Antineutrino
(1)
Inverse
beta decay
Neutron
Proton
(2)
Ionization
cascade
γ
e^-
e^+
γ
uv
Terphenyl
(3)
Visible light
Blue
light
Liquid scintillator
Pulse height
analyzer
Oscilloscope
Current



The second version of Reines' experiment that worked

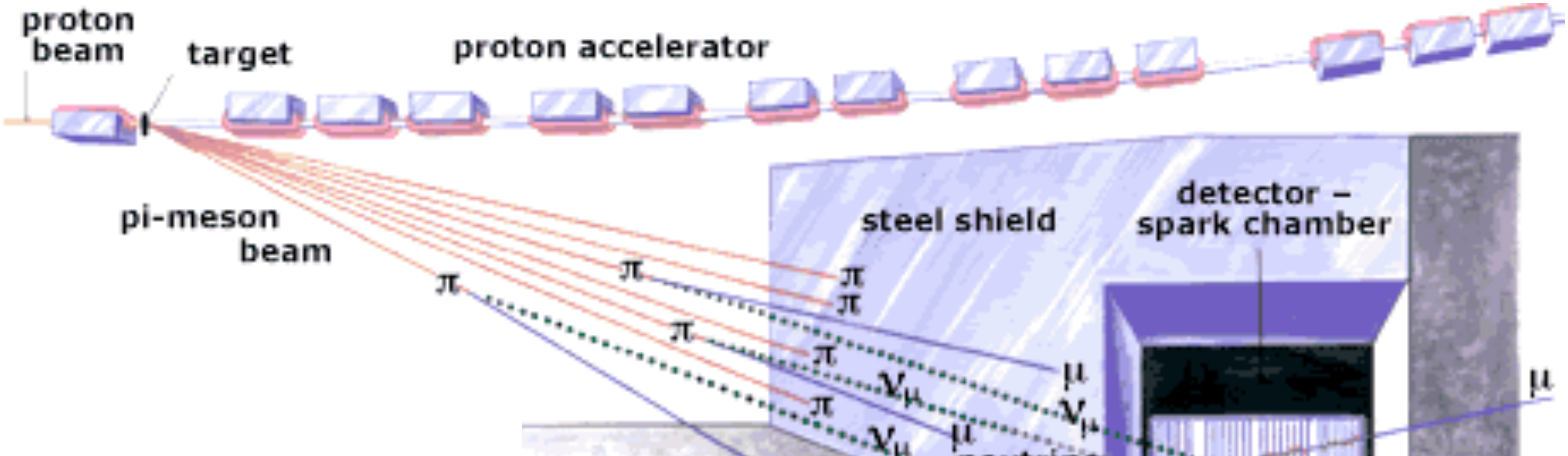
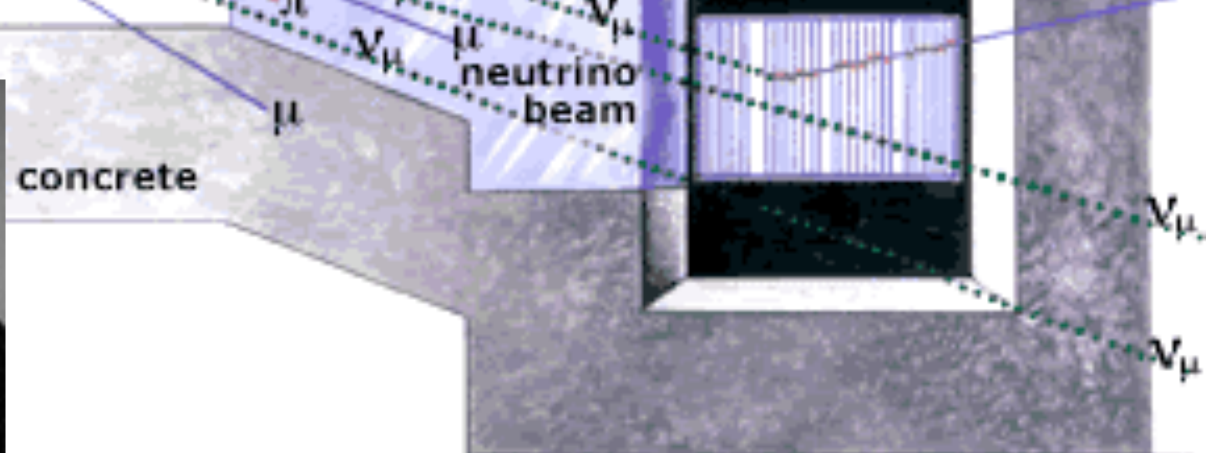

I
II
III
(a) Positron scope
Neutron scope
(b) Positron scope
Neutron scope
(c) Neutron scope
(d) Neutron scope
(e) Positron scope
(f) Neutron scope

The discovery of the second "flavor" of the neutrino

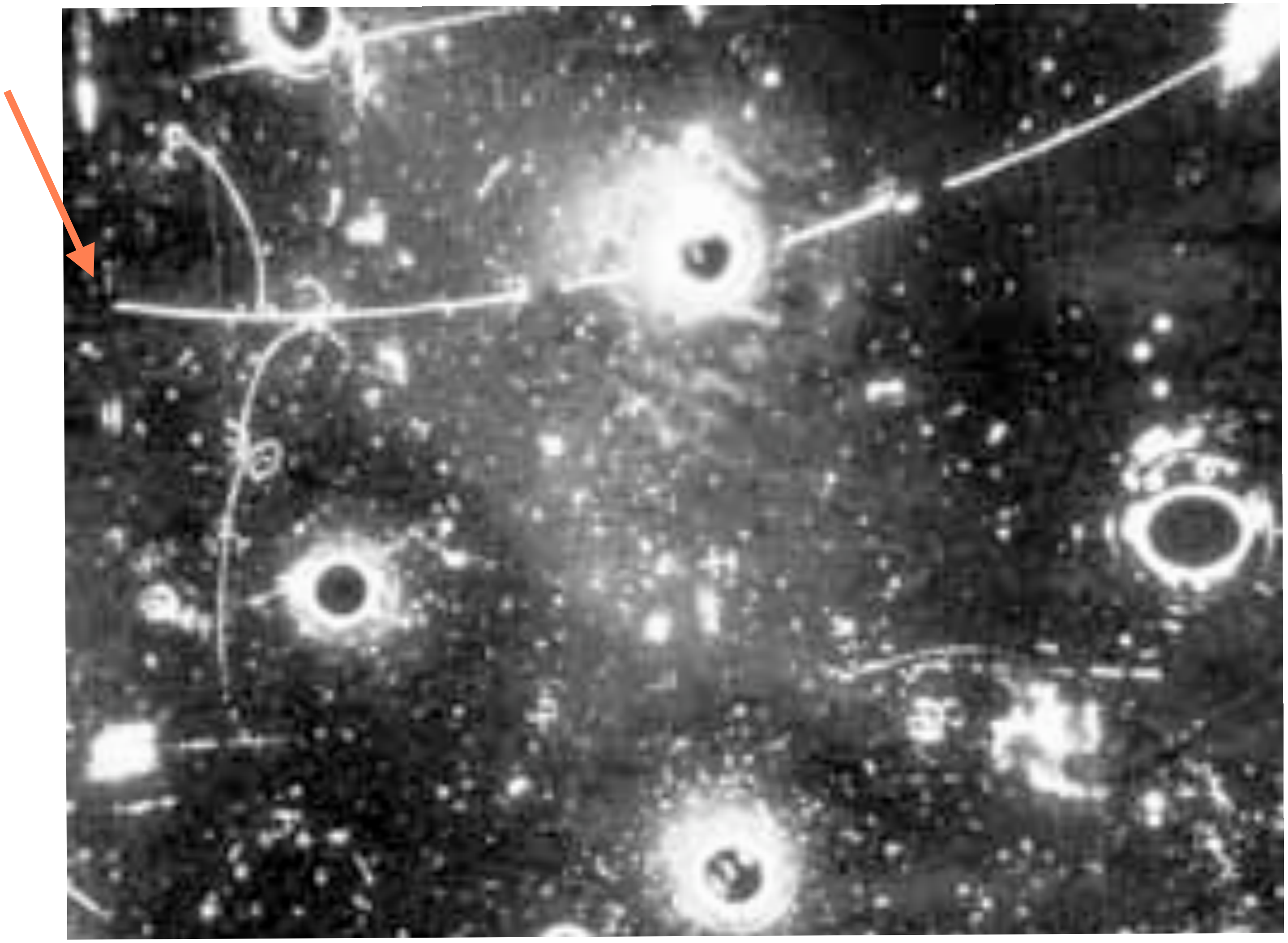
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

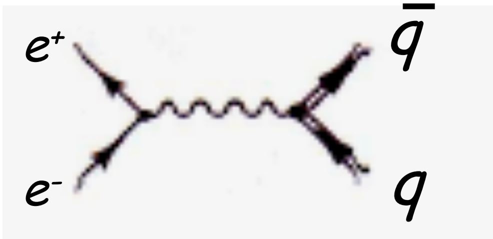
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

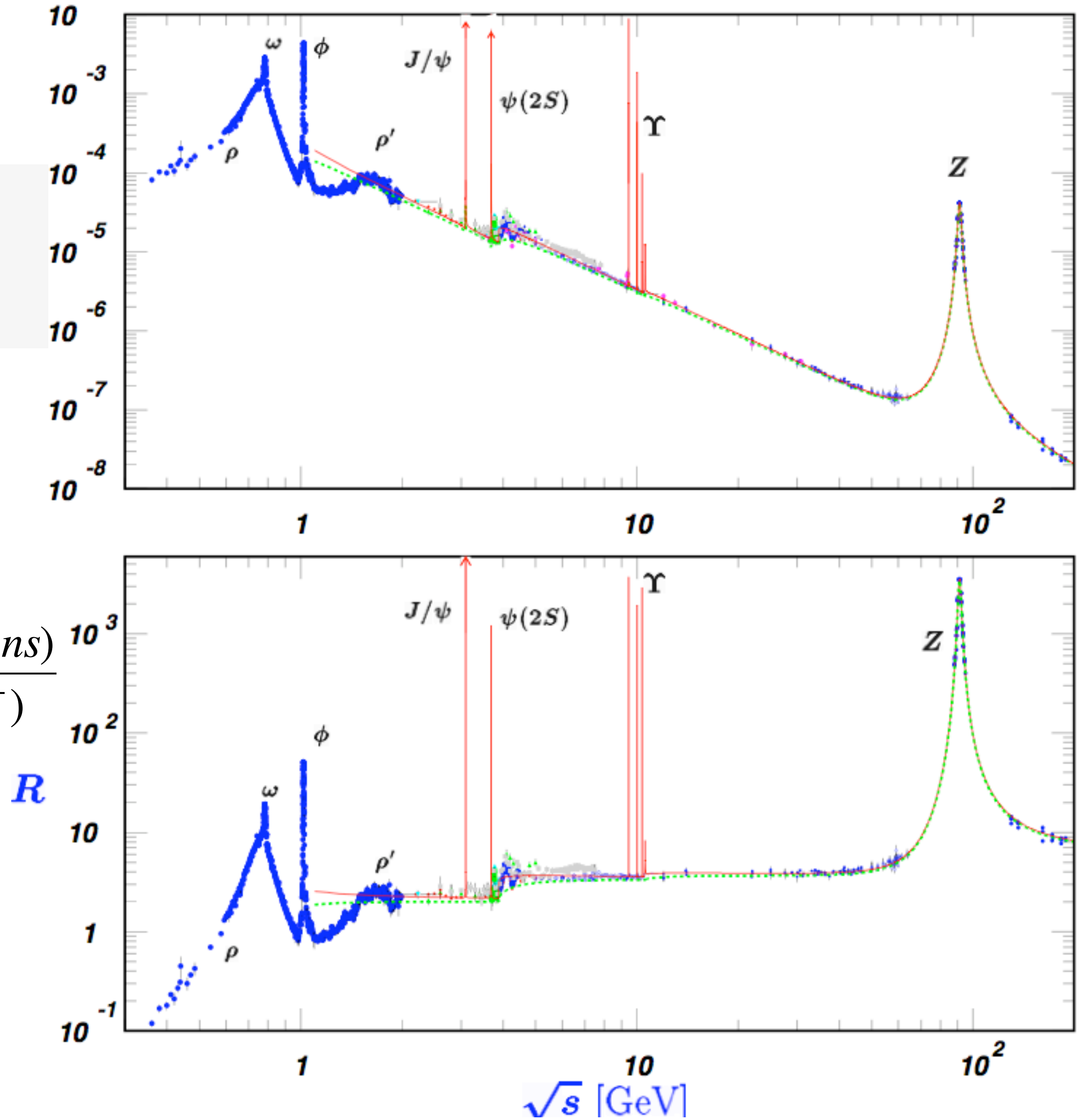
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad \tau \approx 2.2\ \mu\text{sec}$$

Neutral Currents



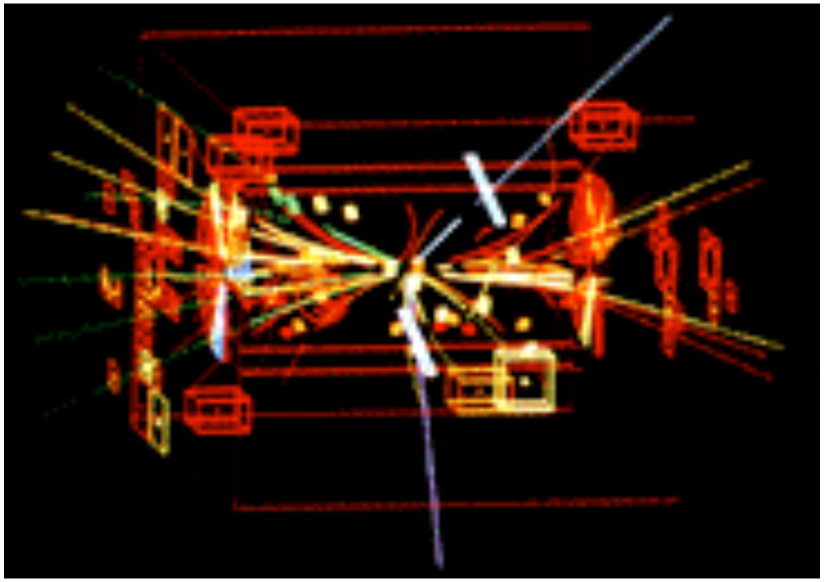




$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

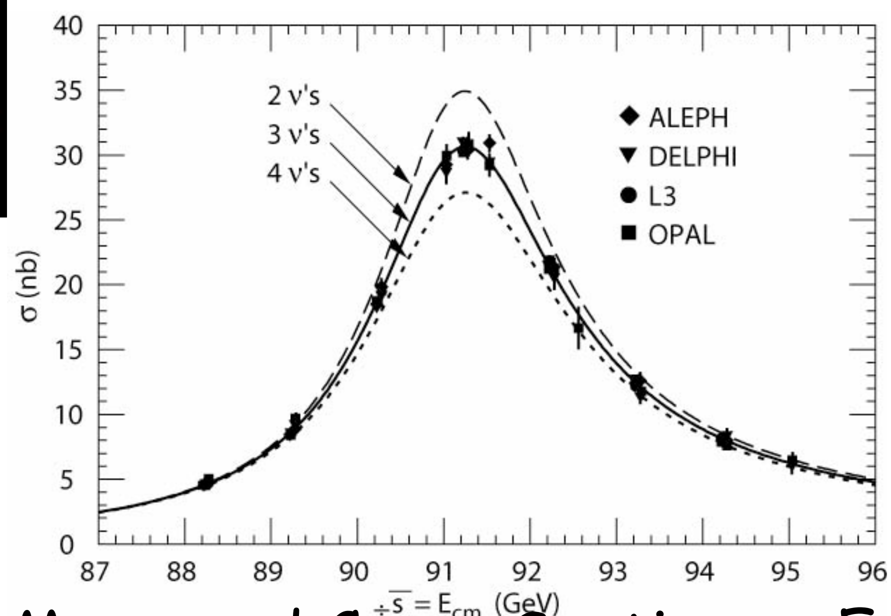
$$R(E) = 3\sum Q_i^2$$

Determining the number of ("active" "light") neutrinos by measuring the width of the Z^o



First Z^o event at LEP

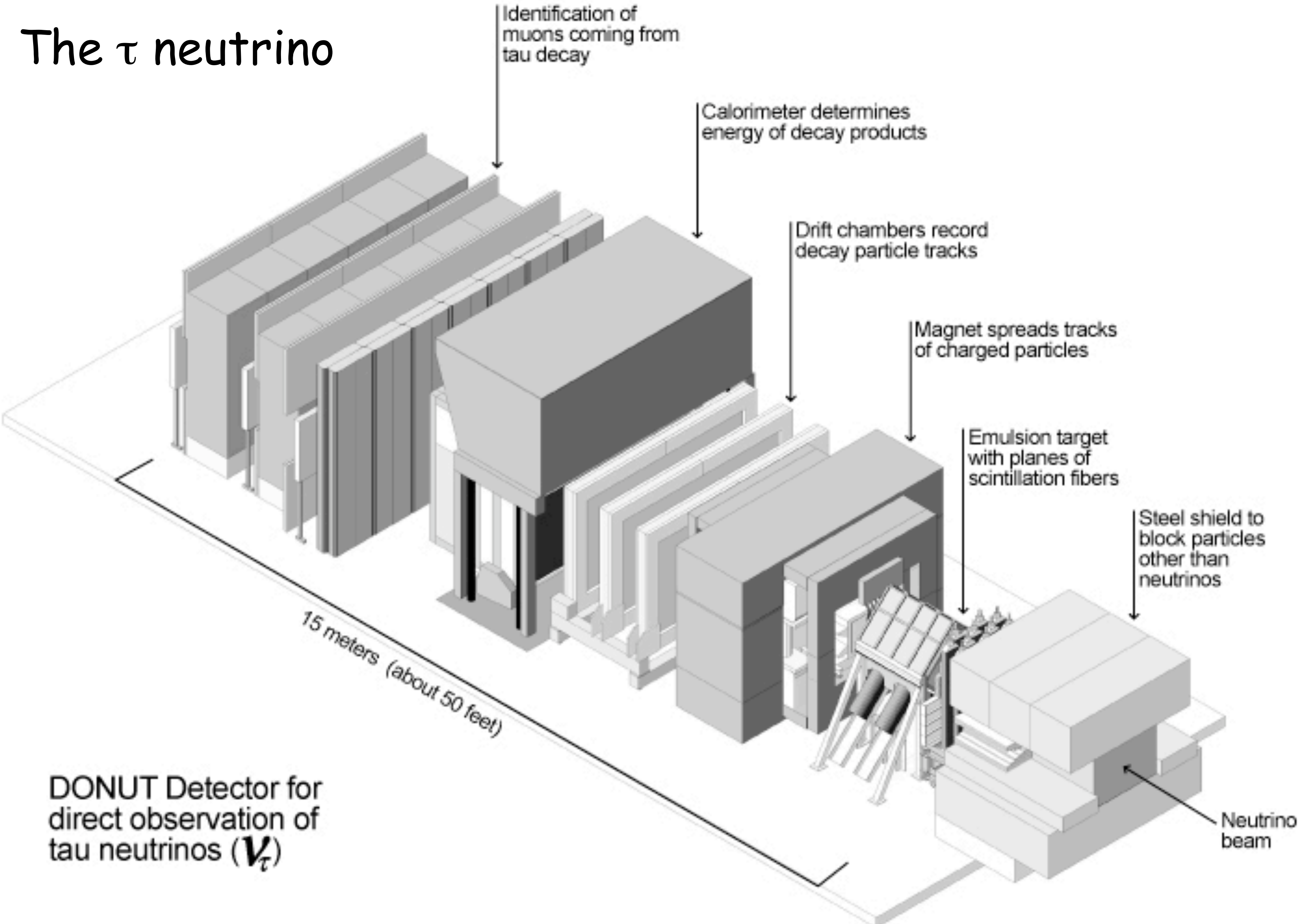
$$Z^o \rightarrow q\bar{q}, l\bar{l}$$



Measured Cross Section vs E_{cm}

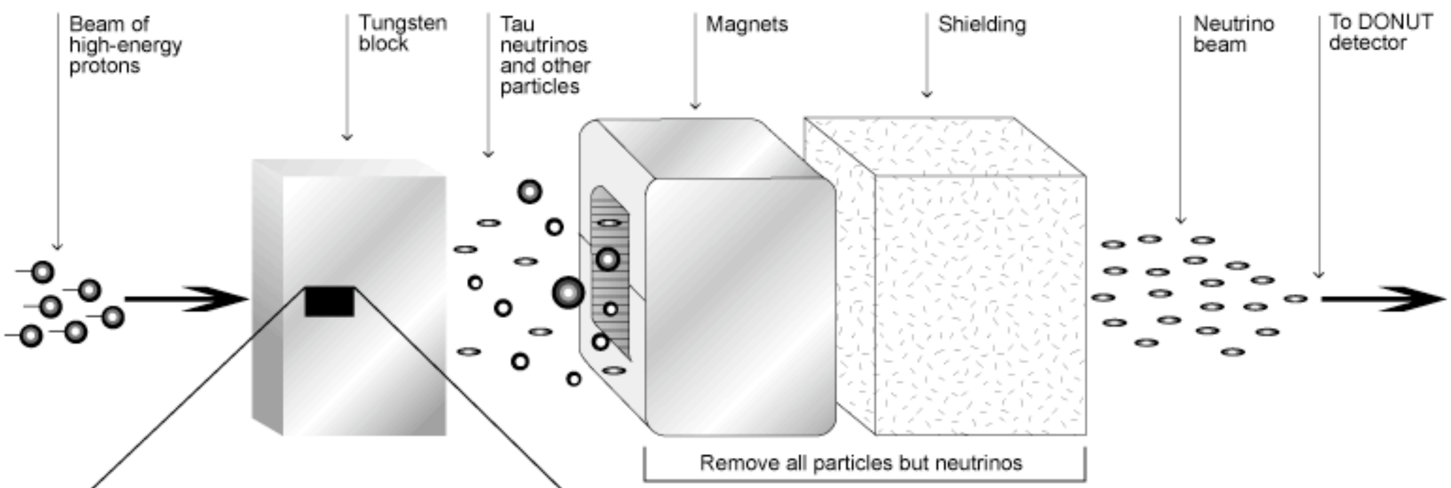
DONUT Detector

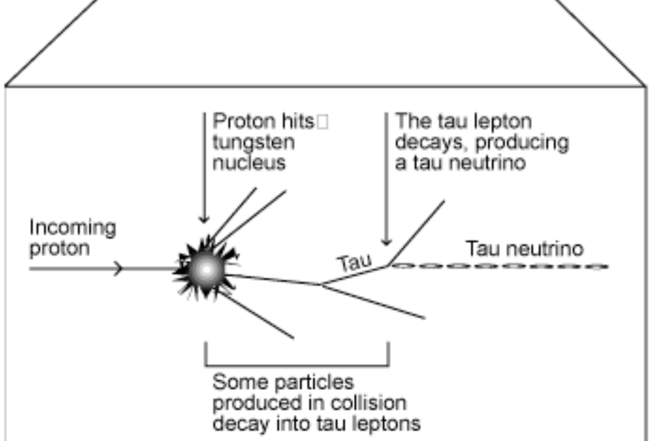
The τ neutrino



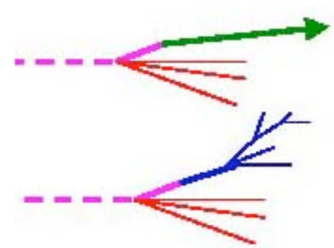
DONUT Detector for direct observation of tau neutrinos (ν_τ)

Creating a Tau Neutrino Beam





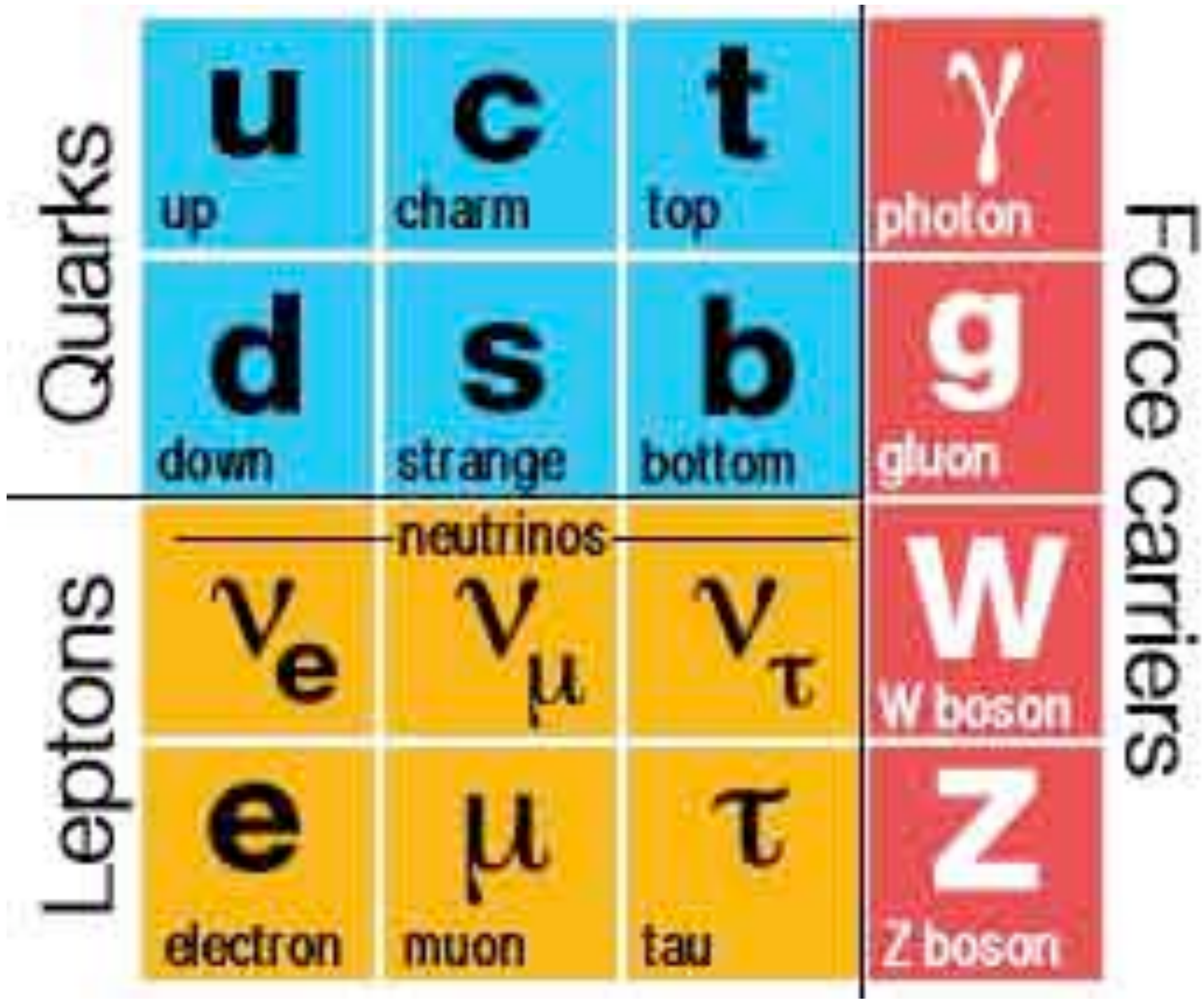
The τ is identified by its relatively long lifetime



ν_τ CC → 18% BF to a penetrating muon → *long* event

ν_τ CC → 18% BF to an electron → *short* event

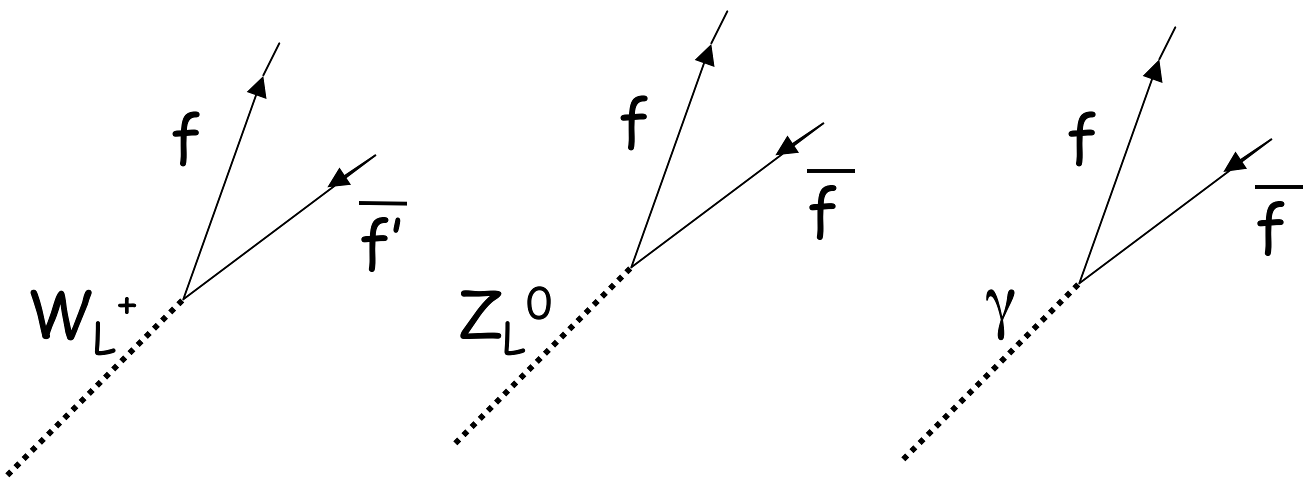
The Standard Model of Quarks and Leptons



Electroweak Fermions
(massless neutrinos)

quarks $\begin{pmatrix} u_L \\ d_L' \end{pmatrix} \begin{pmatrix} c_L \\ s_L' \end{pmatrix} \begin{pmatrix} t_L \\ b_L' \end{pmatrix}$ $(d_R')(u_R)\ (s_R')(c_R)\ (b_R')(t_R)$

leptons $\begin{pmatrix} e_L \\ \nu_{eL} \end{pmatrix} \begin{pmatrix} \mu_L \\ \nu_{\mu L} \end{pmatrix} \begin{pmatrix} \tau_L \\ \nu_{\tau L} \end{pmatrix}$ $(e_R)\quad(\mu_R)\quad(\tau_R)$



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \text{ and } s_{ij} = \sin\theta_{ij}$$

CKM mixing matrix

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

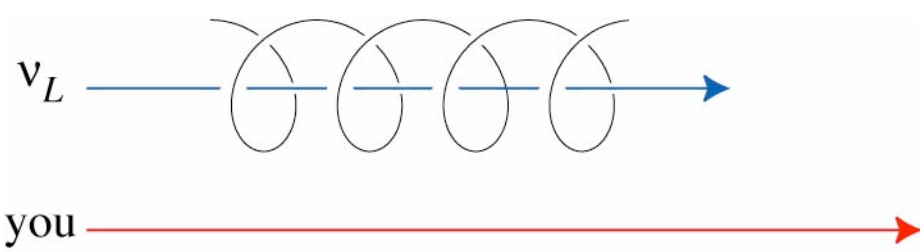
$$\begin{pmatrix} 0.9741 \text{ to } 0.9756 & 0.219 \text{ to } 0.226 & 0.0025 \text{ to } 0.0048 \\ 0.219 \text{ to } 0.226 & 0.9732 \text{ to } 0.9748 & 0.038 \text{ to } 0.044 \\ 0.004 \text{ to } 0.014 & 0.037 \text{ to } 0.044 & 0.9990 \text{ to } 0.9993 \end{pmatrix}$$

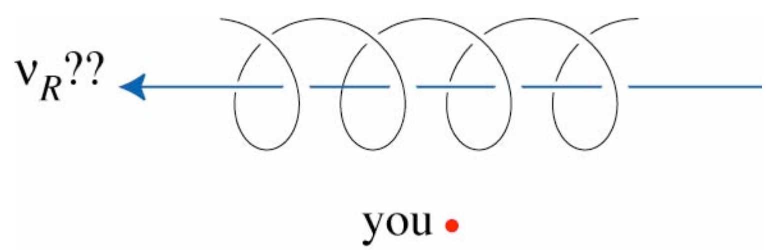
Mixing angles are small!

Helicity of Neutrinos*

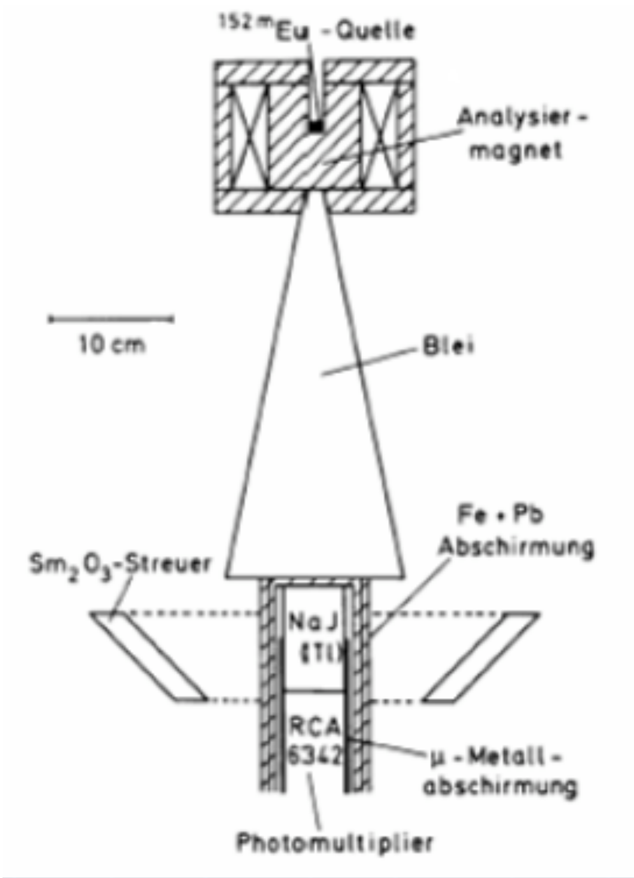
M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

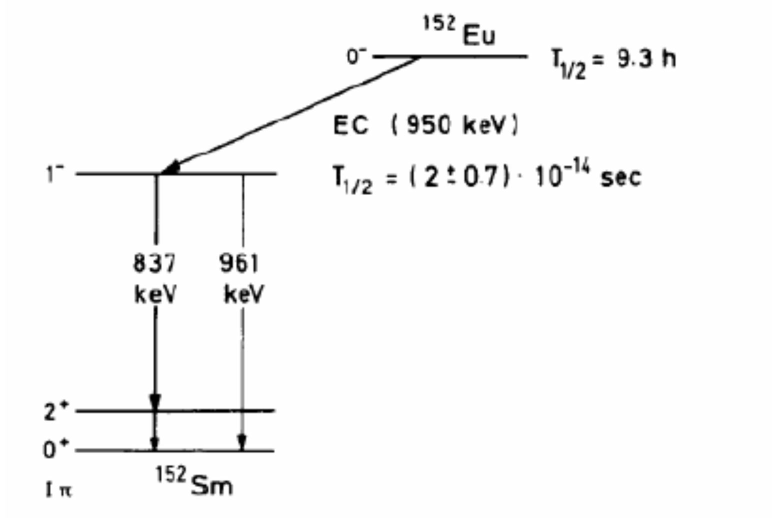
A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

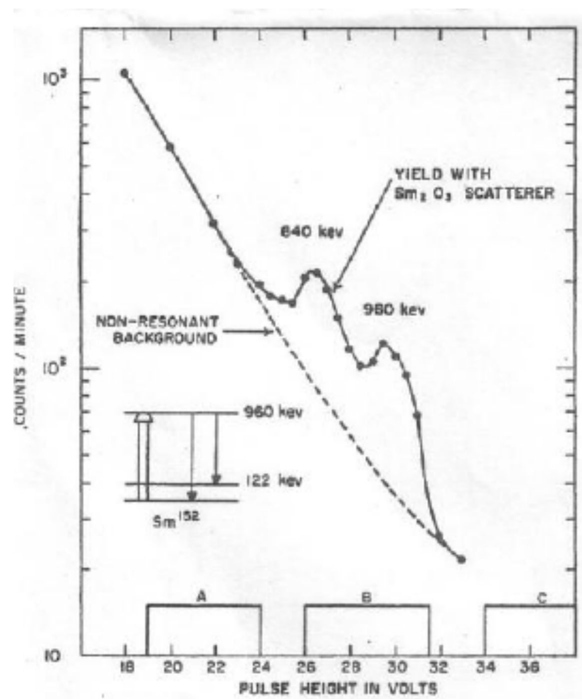




Elements of the Goldhaber-Grodzin-Sunyar experiment







Homework assignment

Quarks

$$\begin{pmatrix} u_L \\ d'_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s'_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b'_L \end{pmatrix}$$

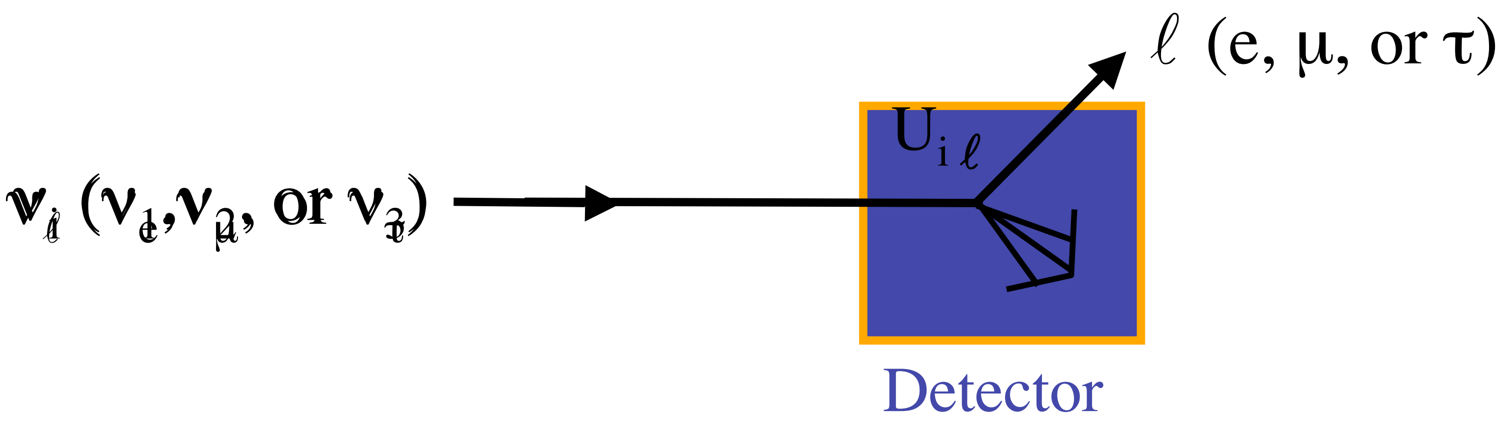
$$|d'_L> = V_{ud}\,|d_L> + V_{us}\,|s_L> + V_{ub}\,|b_L>$$

Leptons

$$\begin{pmatrix} e_L \\ \nu_{eL} \end{pmatrix} \quad \begin{pmatrix} \mu_L \\ \nu_{\mu L} \end{pmatrix} \quad \begin{pmatrix} \tau_L \\ \nu_{\tau L} \end{pmatrix}$$

$$|\nu_{eL}> = U_{e1}\,|\nu_{1L}> + U_{u2}\,|\nu_{2L}> + U_{u3}\,|\nu_{3L}>$$

Leptonic Mixing and Leptonic Flavor



A neutrino that can only create a e is called a ν_e.

A neutrino that can only create a μ is called a ν_μ.

A neutrino that can only create a τ is called a ν_τ.

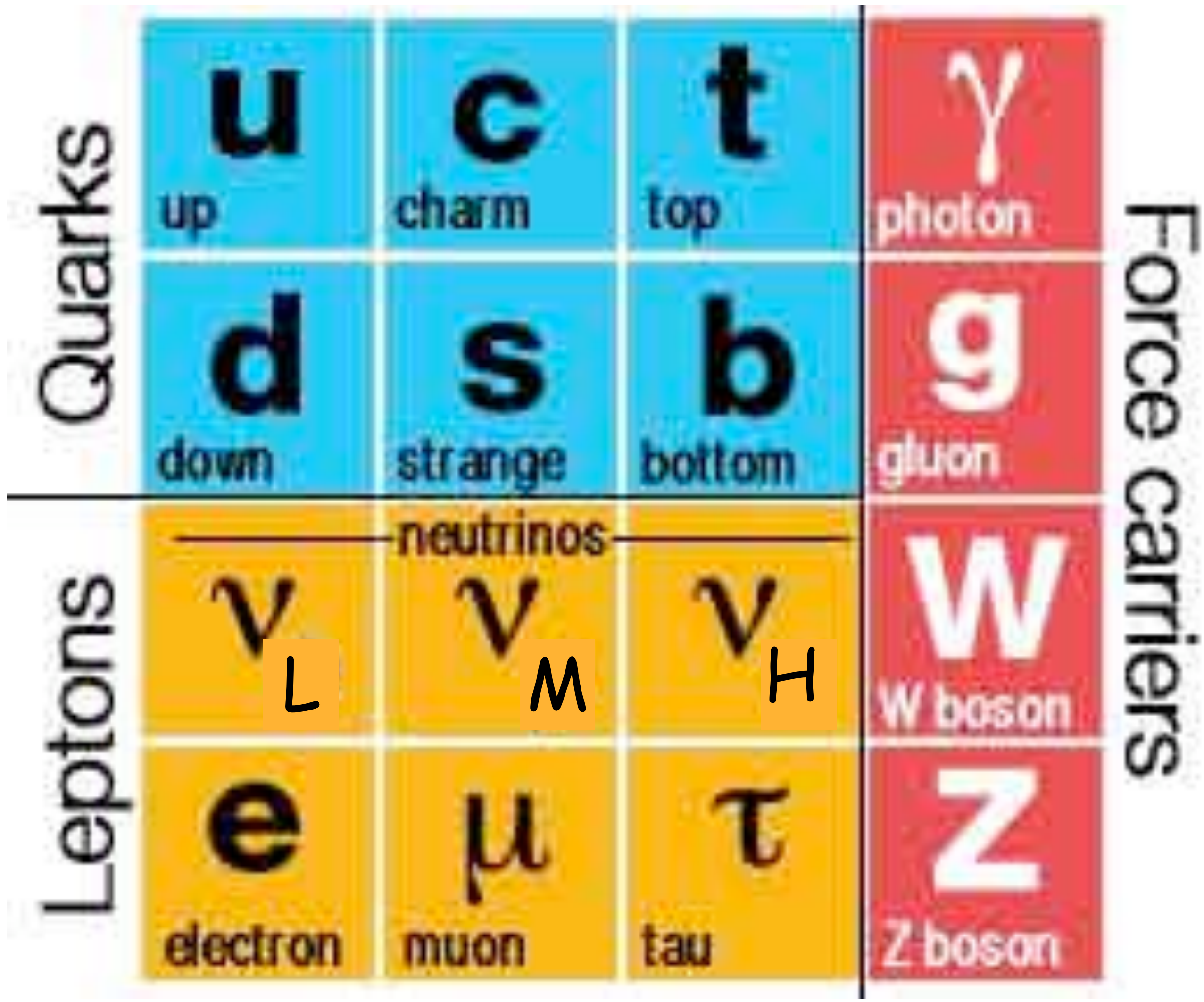
ν_e, ν_μ, and ν_τ are the "neutrinos" with different "flavors"

Any mass eigenstate ν_i is a sum of ν_e, ν_μ, and ν_τ.

ν_e, ν_μ, and ν_τ are each the sum of ν_1, ν_2 and ν_3.

(Kayser)

The (new) Standard Model of Quarks and Leptons
(with massive neutrinos)



(preview)

Neutrino mixing matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}$$

$\theta_{23} = (45 \pm 7)^\circ$

$\theta_{13} < 13^\circ$

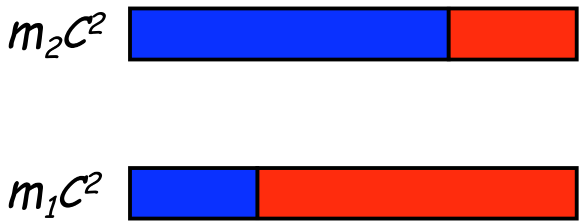
$\delta = ?$

$\theta_{12} = (33.9^{+2.4}_{-2.2})^\circ$

$\alpha = ?$

$\beta = ?$

Essentials of Neutrino Oscillations



$$|\nu_e> = |\psi_{\nu_e}(0)> = \cos\theta\,|\nu_1> + \sin\theta\,|\nu_2>$$

$$|\psi_{\nu_e}(t)> = \cos\theta e^{-\frac{im_1c^2t}{\hbar}}\,|\nu_1> + \sin\theta e^{-\frac{im_2c^2t}{\hbar}}\,|\nu_2>$$

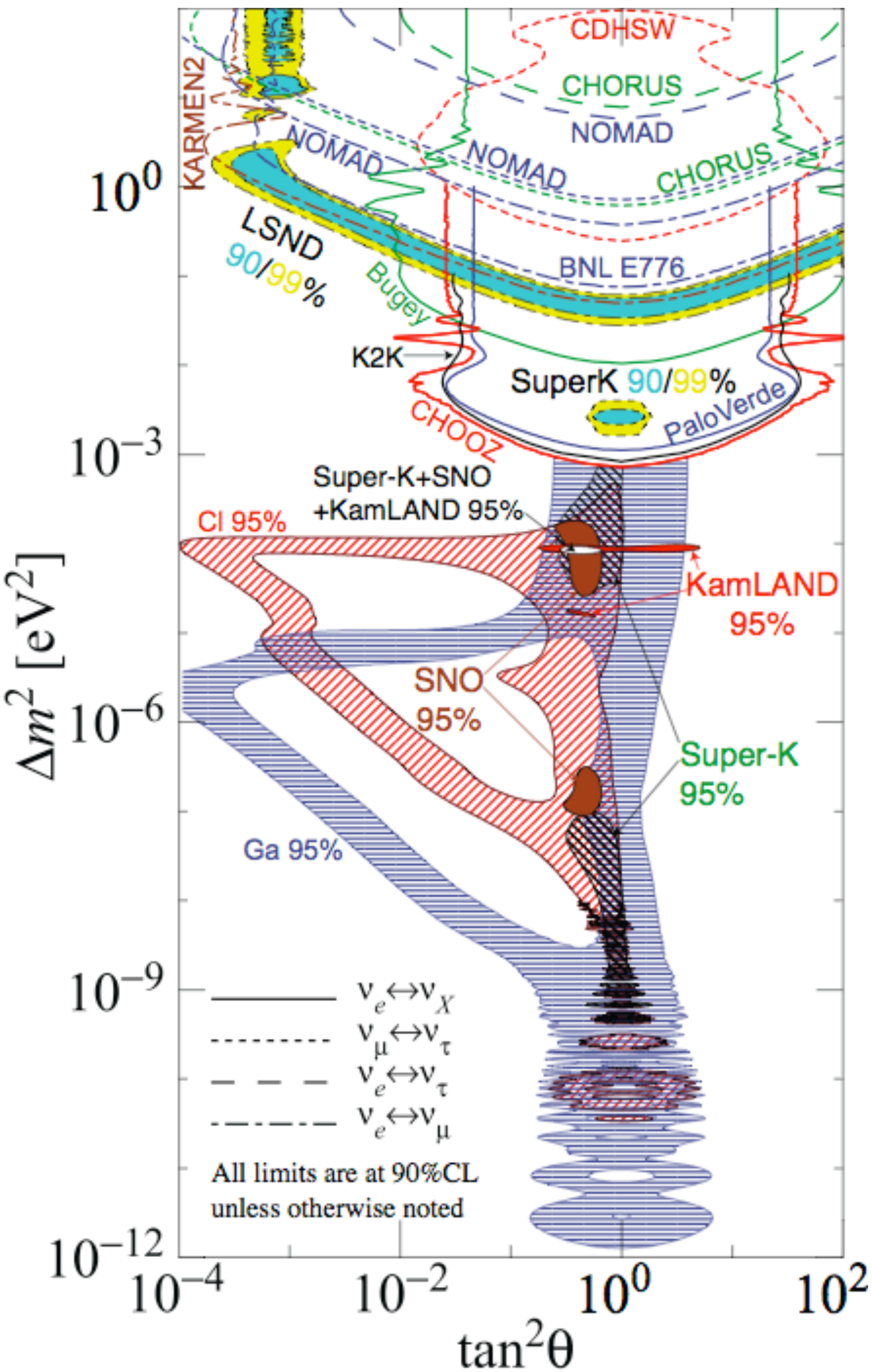
$$P_{ee}(t) = \left|<\psi_{\nu_e}(0)\,|\psi_{\nu_e}(t)>\right|^2 = \left|\cos^2\theta e^{-\frac{im_1c^2t}{\hbar}} + \sin^2\theta e^{-\frac{im_2c^2t}{\hbar}}\right|^2$$

$$P_{ee}(t) = 1 - \sin^2 2\theta \sin^2\left(\frac{(m_2 - m_1)c^2}{2\hbar}t\right)$$

$$t = \frac{t_{lab}}{\gamma} \approx \frac{L}{\gamma c} \qquad \gamma = \frac{E}{mc^2} \qquad m = \frac{m_1 + m_2}{2}$$

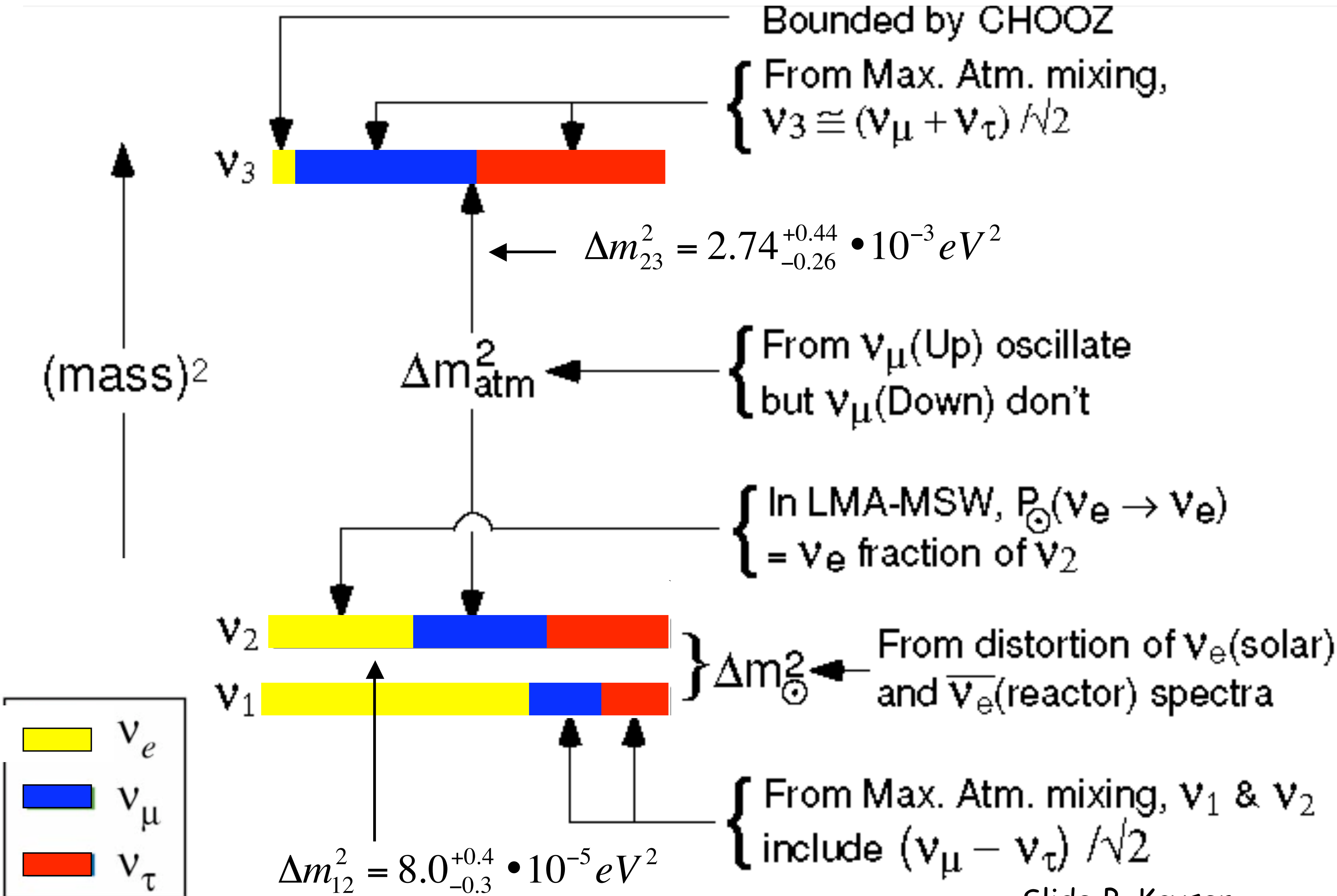
$$P_{ee}(L) = 1 - \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)c^4}{4\hbar c}\frac{L}{E}\right)$$

$$P_{ee}(L) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

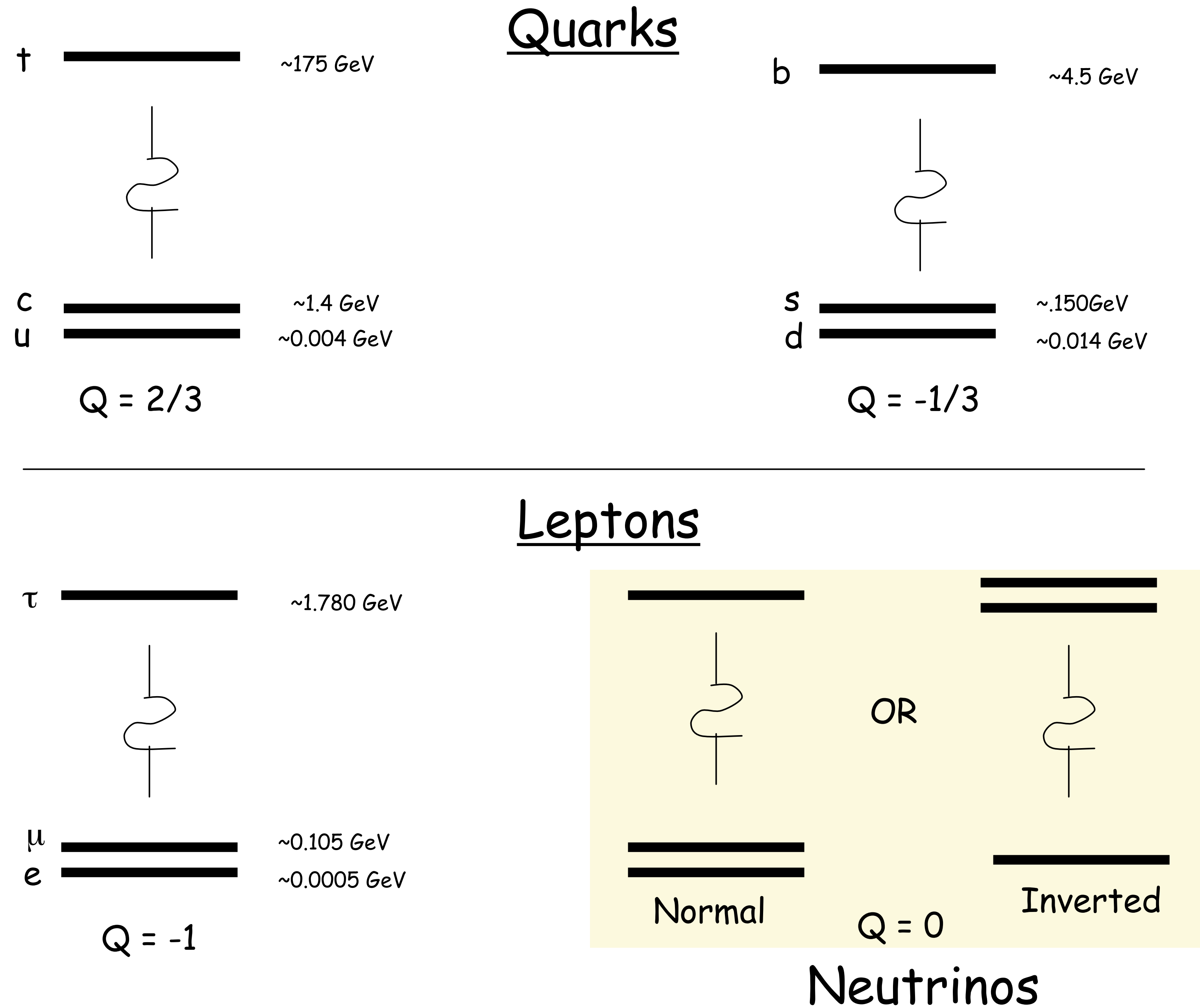


CDHSW
CHORUS
NOMAD
KARMEN2
NOMAD
NOMAD
CHORUS
LSND
90/99%
Bugey
BNL E776
K2K
SuperK 90/99%
CHOOZ
PaloVerde
Super-K+SNO
+KamLAND 95%
Cl 95%
KamLAND
95%
SNO
95%
Super-K
95%
Ga 95%
$\nu_e \leftrightarrow \nu_X$
$\nu_\mu \leftrightarrow \nu_\tau$
$\nu_e \leftrightarrow \nu_\tau$
$\nu_e \leftrightarrow \nu_\mu$
All limits are at 90%CL
unless otherwise noted
Δm^2 [eV^2]
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-4}
10^{-2}
10^0
10^2
$\tan^2\theta$

(Preview)



Slide B. Kayser


Quarks
t
~175 GeV
c
~1.4 GeV
u
~0.004 GeV
Q = 2/3
b
~4.5 GeV
s
~.150GeV
d
~0.014 GeV
Q = -1/3
Leptons
τ
~1.780 GeV
μ
~0.105 GeV
e
~0.0005 GeV
Q = -1
OR
Normal
Inverted
Q = 0
Neutrinos

What are these objects and what do they have to do with ν?