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Neutrino Physics

Graduate School 1504 „Mass, Spectra, Symmetry“
Automn Block Course, September 9-12, 2012, Berlin

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Neutrinos in the Standard Model of Particle Physics

Neutrino oscillations:
experiments with atmospheric,
solar, accelerator and reactor neutrinos

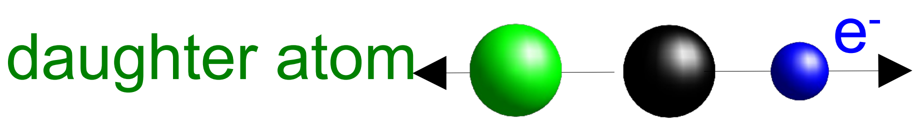
Neutrino masses:
- cosmology and astrophysics
- neutrinoless double β decay
- direct neutrino mass experiments

Neutrino telescopes

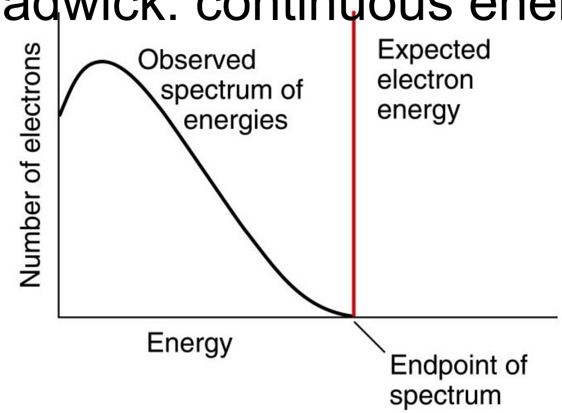
Pauli`s neutrino hypothesis

1914 β decay:

mother atom

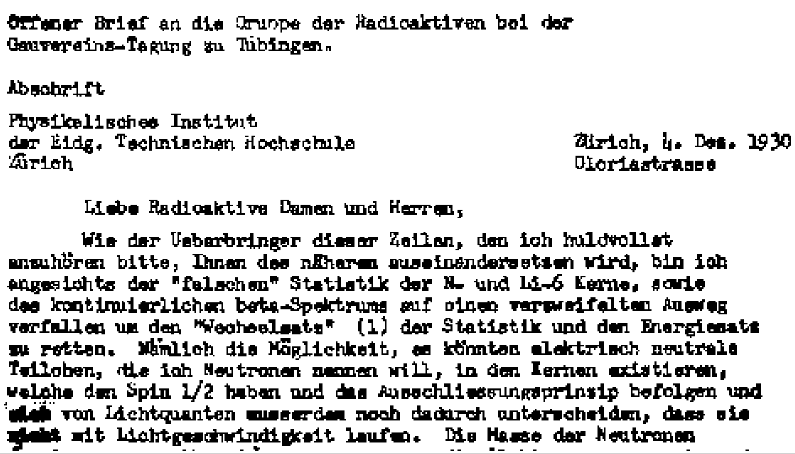


Chadwick: continuous energy spectrum of emitted e^-



⇒ looks like a violation of the energy and (angular momentum) conservation

1930: Wolfgang Pauli postulates neutrino ν neutral, spin 1/2, very light or massless



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

Abschrift

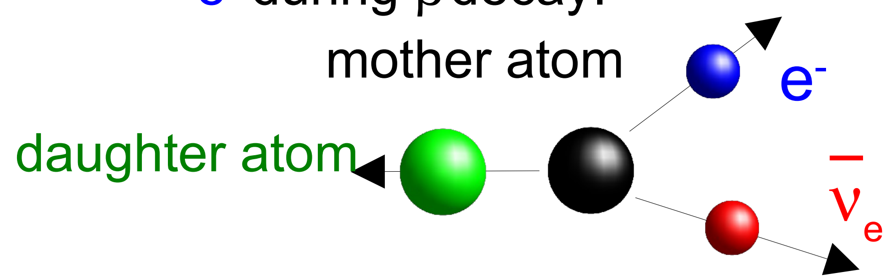
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

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

⇒ ν is emitted in addition to the e^- during β decay:



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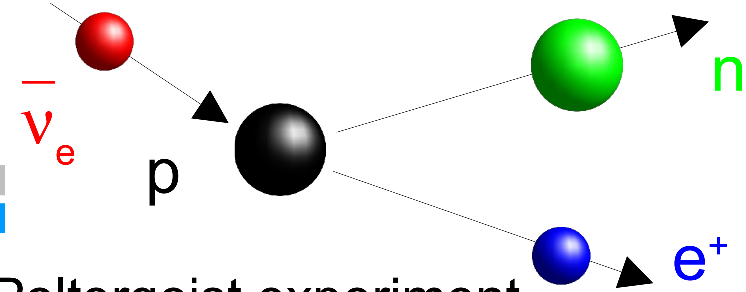
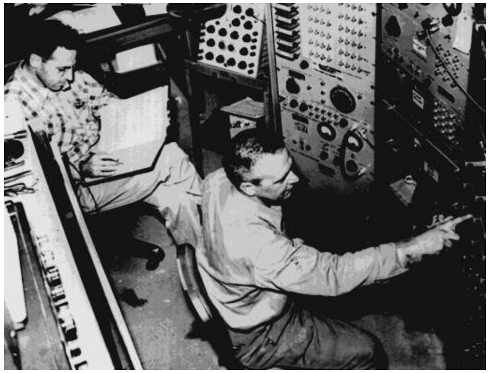
Experimental proof of neutrinos





1956: Cowan and Reines: Poltergeist experiment

strong $\bar{\nu}_e$ source: nuclear power reactor:

6 $\bar{\nu}_e$/fission (from fission products), $E_\nu < 9$ MeV

energy gain / fission: 200 MeV

1 GW thermal power $\Rightarrow$ $2 \cdot 10^{20}$ ν/s

Detection reaction: inverse β decay: $\bar{\nu}_e + p \rightarrow n + e^+$ (threshold: 1.8 MeV)

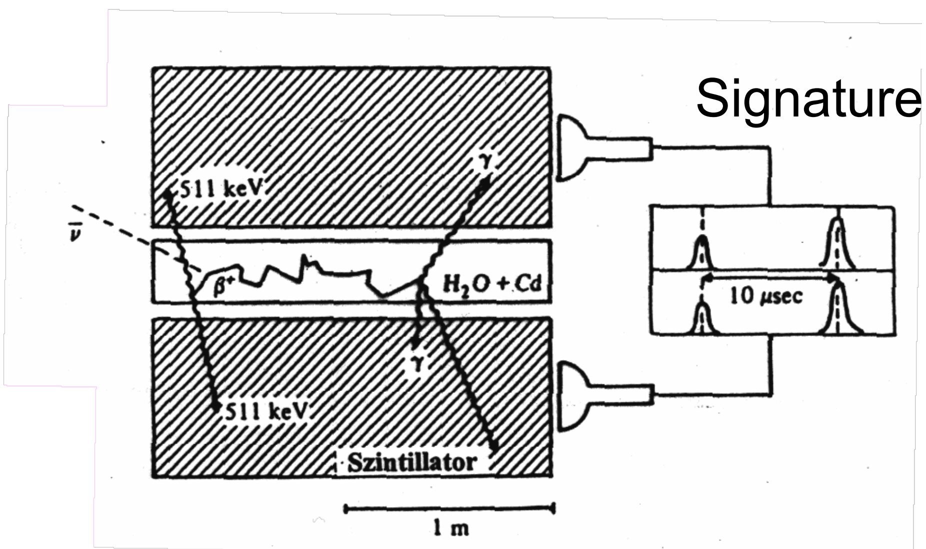


figure: Schmitz: Neutrinophysics, Teubner

Signature: a) n: thermalisation by elastic scattering, capture on Cd $\Rightarrow$ γ's

b) e^+: annihilation $\Rightarrow$ 2γ's (511 keV)

$\Rightarrow$ spatial and time-delayed coincidence (nearly background free)

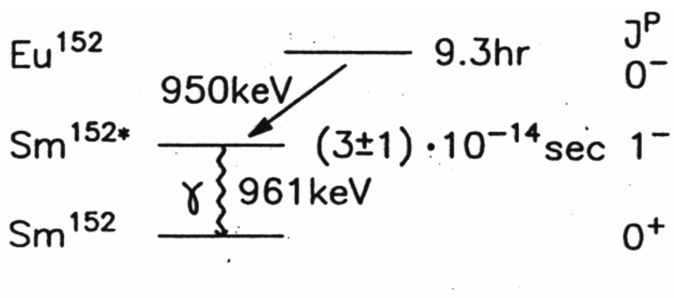
measured cross section:

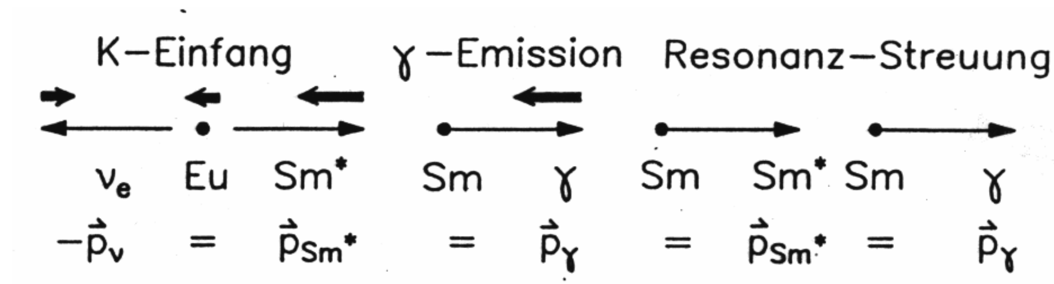
$(1.1 \pm 0.3) \cdot 10^{-43}$ cm^2

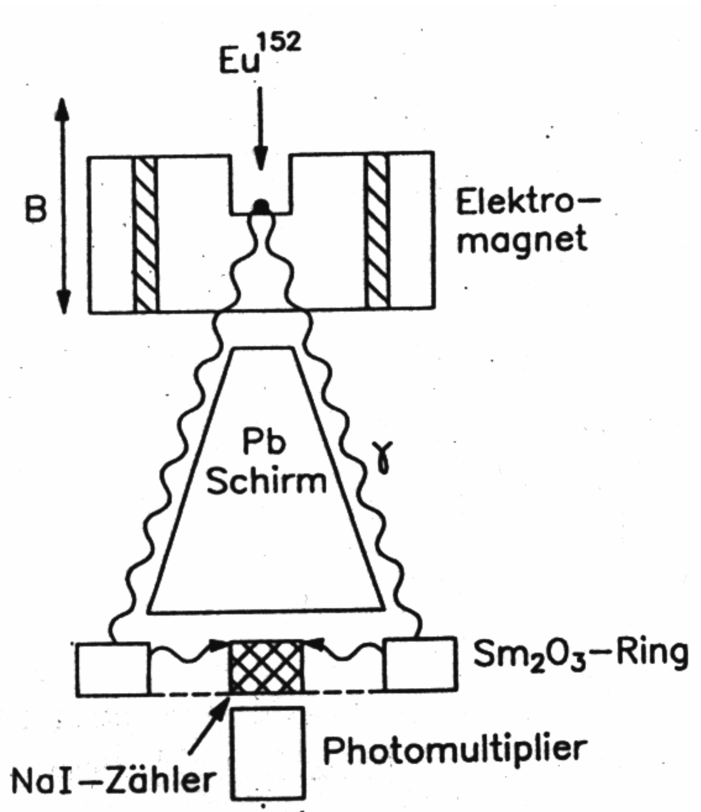
(in good agreement with Fermi`s theory for V-A)

Helicity of the neutrinos: Goldhaber experiment

Helicity: projection of the spin onto flight direction $\mathcal{H} = \vec{\sigma}\,\vec{p} \,/\, |p|$







figures: Schmitz: Neutrinophysics, Teubner

Determination of the helicity of the neutrinos:

- Detect γ by resonance scattering on ^{152}Sm
  Usually not possible due to red shift from γ recoil !
- But resonance scattering is possible,
  if primary ν recoil gives the right blue shift:
  $\Rightarrow$ 180° emission of ν and γ
- Due to spin structure of transissions:
  $\mathcal{H}(\nu) = \mathcal{H}(\gamma)$ for detected photons
- Measure $\mathcal{H}(\gamma)$ by determination of transmission through magnetized iron

Result: $\mathcal{H}(\nu_e) = -1$

Fermi`s theory of the β decay

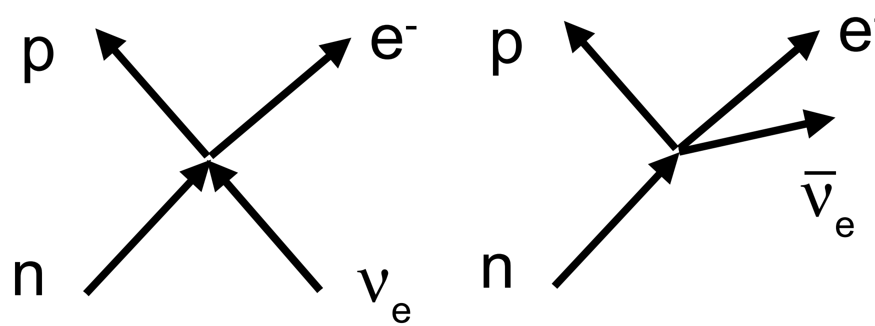
1934 Enrico Fermi formulates theory of the β decay like in electrodynamics:

four point interaction

current-current-coupling $\mathcal{H} = G_F/2 \cdot J_\mu \cdot J^\mu$

hadronic current: $J_\mu = < \bar{p} \,|\, \gamma_\mu \,|\, n >$

leptonic current: $J^\mu = < \bar{e} \,|\, \gamma^\mu \,|\, \nu_e >$



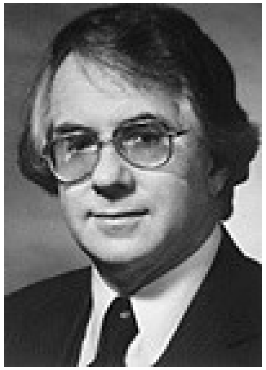
This ansatz is still right as a low-energy approximation,

only the γ_μ operator has to be more generalized due to parity violation:

$$< \bar{e} | \gamma^\mu | \nu_e > \; \rightarrow \; < \bar{e} | \gamma^\mu (1 - \gamma_5) | \nu_e >$$

$$\gamma^\mu - \gamma^\mu \gamma_5 =: V - A$$

ν's in the electroweak Standard Model: U(1)SU(2)



S. Glashow

S. Weinberg

A. Salam

12 fundamental fermions

6 left-handed weak isospin dublets:

Leptonen $\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau \\ \tau^-\end{pmatrix}_L$ pure weak isospin dublets

Quarks $\begin{pmatrix}u \\ d\end{pmatrix}_L \quad \begin{pmatrix}c \\ s\end{pmatrix}_L \quad \begin{pmatrix}t \\ b\end{pmatrix}_L$ weak isospin dublets

9 right-handed weak isospin singulets:

$e^-_R, \mu^-_R, \tau^-_R, u_R, d_R, c_R, s_R, t_R, b_R$ (no ν_R in SM)

$$\Psi_L = P_L\Psi \quad \Psi_R = P_R\Psi \quad P_L = 1/2(1-\gamma_5) \quad P_R = 1/2(1+\gamma_5)$$

massive leptons in charged weak currents (CC):

- lepton:

  $P(\mathcal{H} = \pm 1) = (1 \pm (-v/c))/2$

  $\Rightarrow P_{Long} = -v/c$

- anti lepton:

  $P(\mathcal{H} = \pm 1) = (1 \pm v/c)/2$

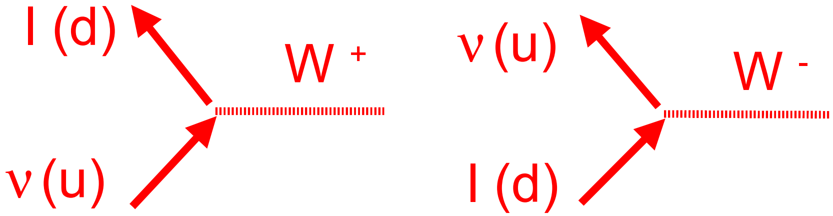
  $\Rightarrow P_{Long} = v/c$

For masseless particles (ν in SM):

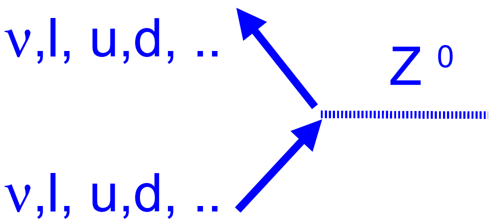
Ψ_L, Ψ_R^c have helicity $\mathcal{H}$ = -1 $\quad \Leftarrow \sigma \quad \rightarrow p$

Ψ_R, Ψ_L^c have helicity $\mathcal{H}$ = +1 $\quad \Rightarrow \sigma \quad \rightarrow p$

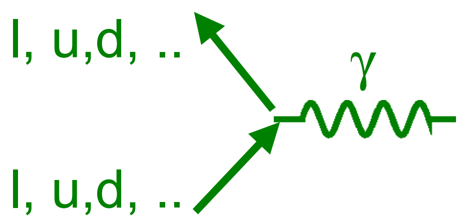
Lagrangian: Interaction part



$$\mathcal{L} = \underbrace{\frac{g}{\sqrt{2}}\left(J_\mu^- W^{+\mu} + J_\mu^+ W^{-\mu}\right)}_{\text{weak charged current (CC)}}$$



$$+ \underbrace{\frac{g}{\cos\theta_W}\left(J_\mu^3 - \sin^2\theta_W J_\mu^{e.m.}\right) Z^{o\mu}}_{\text{weak neutral current (NC)}}$$



$$+ \underbrace{g \sin\theta_W J_\mu^{e.m.} A^\mu}_{\text{em neutral current}} \quad \ldots$$

coupling to electromagnetic current $J_\mu^{e.m.}$ as in QED: $g \sin\theta_W = e$

$\theta_W = 28.7°$ ⇒ coupling of weak interaction ≈ coupling of em. interaction,

but there is a term „m_W^2" (m_Z^2) in the denominator of the propagator, see later

Weakness of weak interaction

Difference ν versus electron scattering

Remember photon propagator:

γ

$$\frac{g_\alpha^{\ \beta}}{q^2} \rightarrow \frac{1}{Q^2}$$

But W propagator:

W

$$\frac{i \cdot g_\alpha^{\ \beta} - \frac{q_\alpha \cdot q^\beta}{M_W^2}}{q^2 - M_W^2} \overset{q^2 \ll M_W^2}{\rightarrow} \frac{-i \cdot g_\alpha^{\ \beta}}{M_W^2} = \text{const.}$$

$\Rightarrow$ weak cross section increases linearly with s,

but is much smaller due to $1/M_W^4$ ($M_W \approx 80$ GeV)

ν cross sections

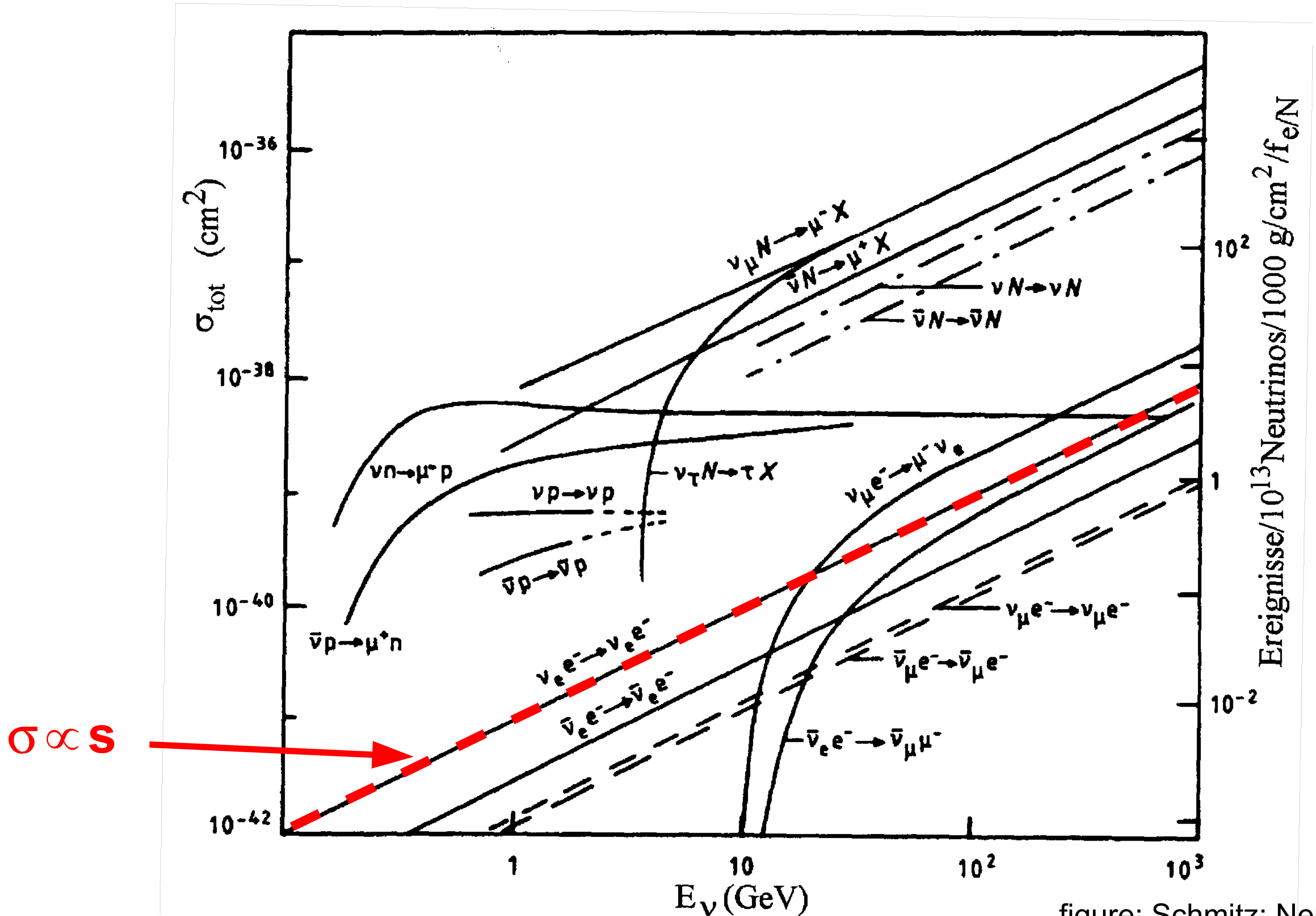


figure: Schmitz: Neutrinophysics, Teubner

ν-fermion scattering cross sections: $\sigma \propto s = m_f^2 + 2E_\nu m_f, \Rightarrow s \propto E_\nu$

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LEP: determination of number of neutrino generations

LEP:

$e^- + e^+ \rightarrow Z^0\,(\gamma) \rightarrow$

visible:

$e^- + e^+$,
$\mu^- + \mu^+$,
$\tau^- + \tau^+$,
$u + \bar{u}$,
$d + \bar{d}$,
$s + \bar{s}$,
$c + c$,
$b + \bar{b}$,

invisible:

$\nu_e + \bar{\nu}_e$,
$\nu_\mu + \bar{\nu}_\mu$,
$\nu_\tau + \bar{\nu}_\tau$,
????

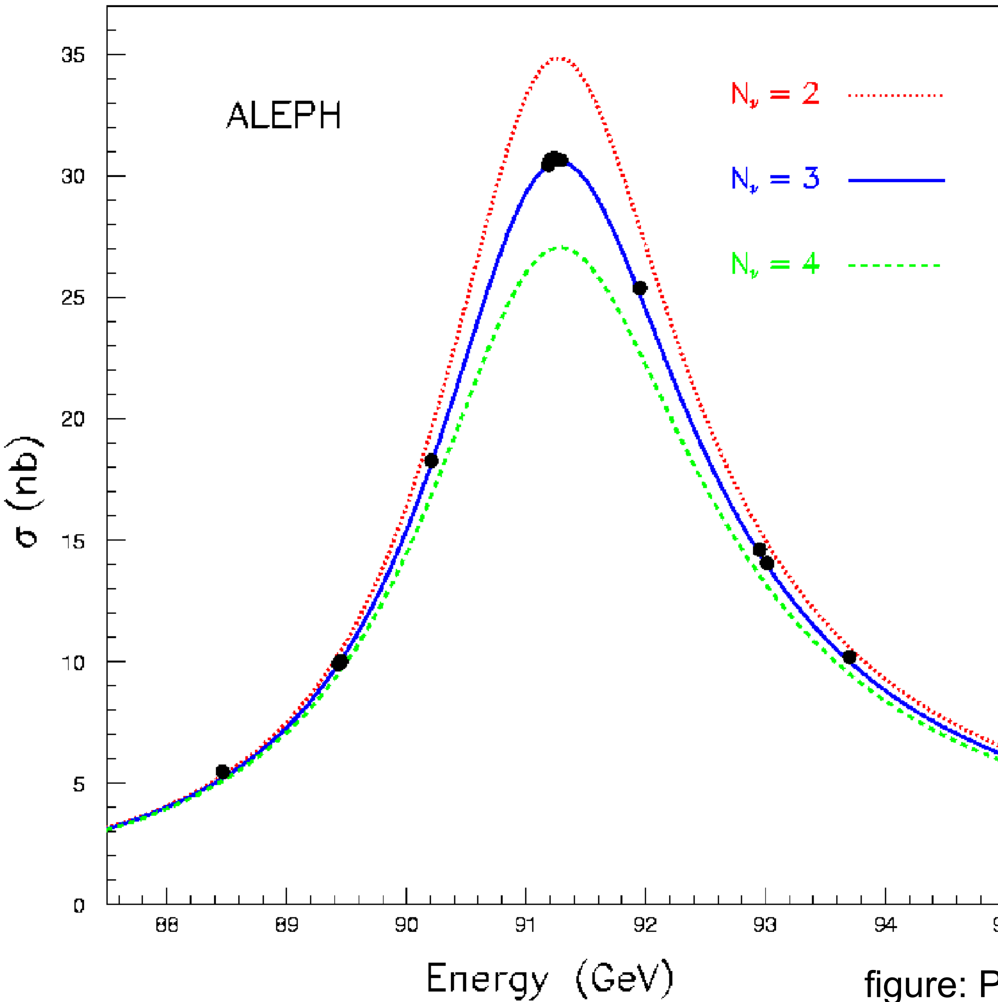


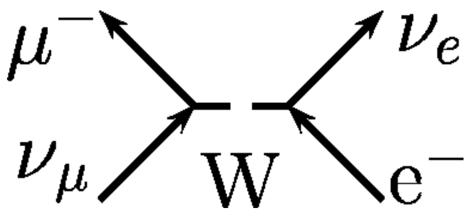
figure: PDG

Exp:

full width:	Γ	= 2495(2) MeV
invisible width:	$\Gamma_{invisible}$	= 499(2) MeV
ν partial width	Γ_ν	= 167.1 MeV $\Rightarrow N_\nu = 2.99$

Angular distribution of neutrino-fermion scattering

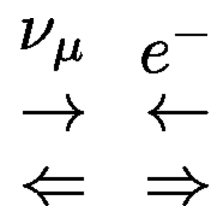
Neutrino-fermion scattering:



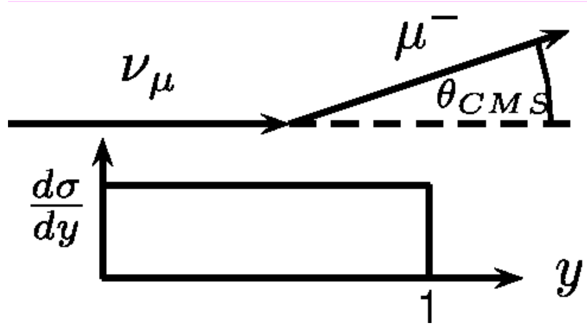
$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2} \cdot s \qquad (q^2 \ll M_W^2)$$

no angular dependence:

$$(\nu_\mu e^- \rightarrow \mu^- \nu_e)$$



$$J = 0$$



$$y = \frac{1 - \cos(\theta_{CMS})}{2}$$

y distribution is flat for νl scattering !

Angular distribution of antineutrino-fermion scattering

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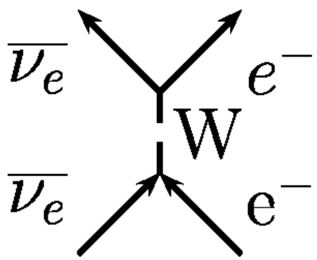
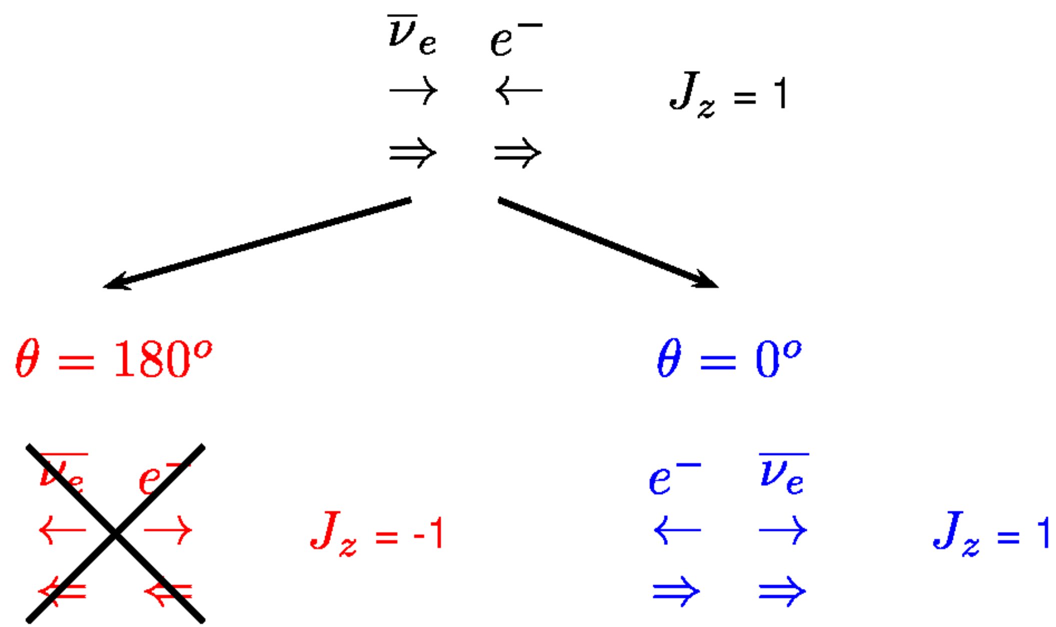
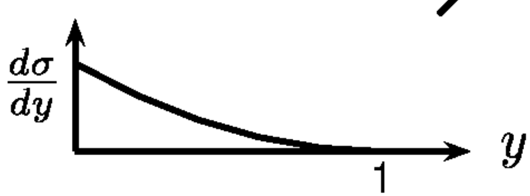
Antineutrino-fermion scattering (neglect NC):



$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2} \cdot s \cdot (1-y)^2$$

angular dependence:





y distribution $\Rightarrow \sigma_{\bar{\nu}l} = 1/3 \cdot \sigma_{\nu l}$

y distribution is not flat for $\bar{\nu}$l scattering !

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Deep inelastic (anti)neutrino-nucleon scattering

Average: $\langle (1-y)^2 \rangle = 1/3$

$\Rightarrow$ expect: $\sigma^{\nu l} = 3\sigma^{\bar{\nu} l}$ and $\sigma^{\nu N} = 3\sigma^{\bar{\nu} N}$

Experiment:

$\sigma^{\nu l} = 3\sigma^{\bar{\nu} l}$, but $\sigma^{\nu N} \approx 2\sigma^{\bar{\nu} N} < 3\sigma^{\bar{\nu} N}$

From helicity arguements we deduce for the y distribution and for σ_{tot}:

$\bar{\nu} q = \nu \bar{q}$ and $\nu q = \bar{\nu} \bar{q}$

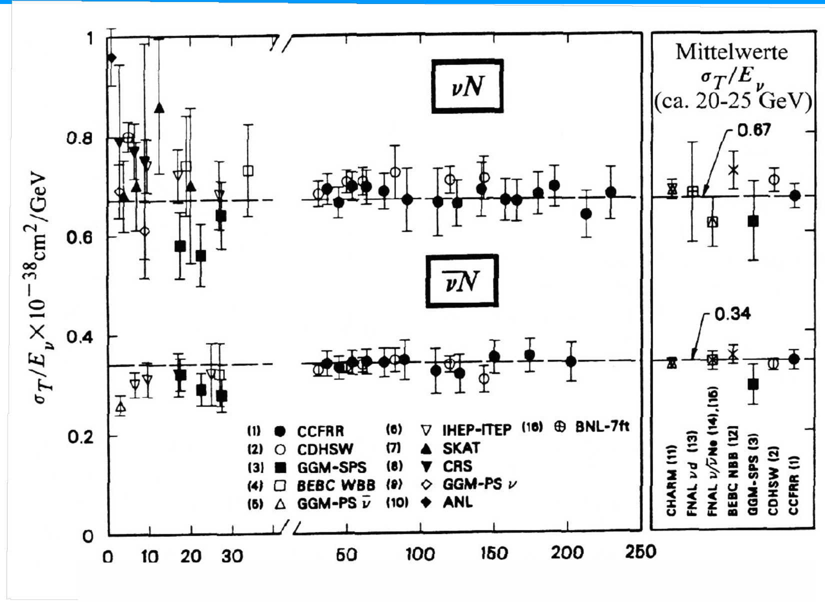
$$\frac{d^2\sigma^{\nu N}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi} \left(q(x) + (1-y)^2 \bar{q}(x) \right)$$

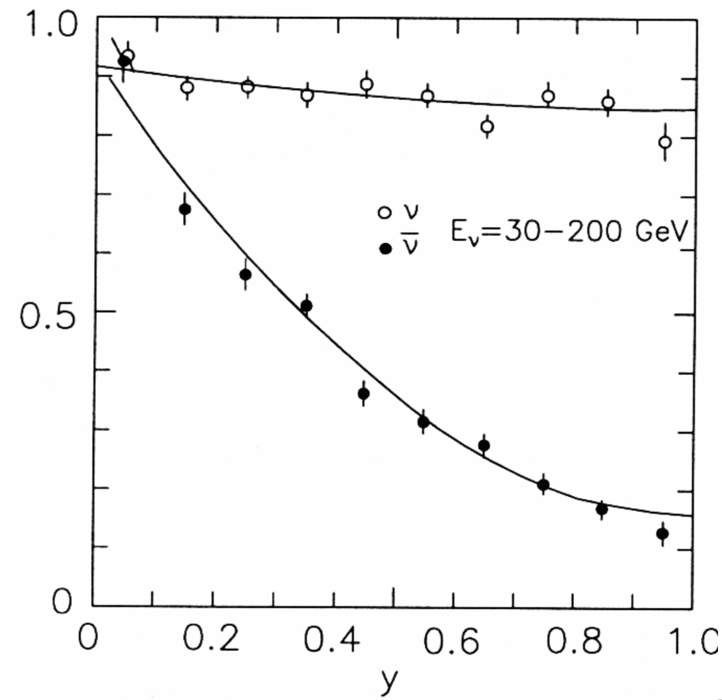
$$\frac{d^2\sigma^{\bar{\nu} N}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi} \left(\bar{q}(x) + (1-y)^2 q(x) \right)$$

with $q(x) = x\,(u(x) + d(x) + s(x) + ...)$

with $\bar{q}(x) = x\,\left(\bar{u}(x) + \bar{d}(x) + \bar{s}(x) + ...\right)$

$\Rightarrow$ Sea quark fraction $\bar{q}(x)$ is about 15%





figures: Perkins: Introduction to High Energy Physics, Cambridge

Results from deep inelastic (anti)neutrino-nucleon scattering

(in addition to deep inelastic charged lepton scattering)

Nucleon consists of partons:

- point-like
- charges of 1/3 and 2/3
- spin ½

Only with neutrinos (or with polarisation d.o.f.):

- there are sea-quarks in the nucleon

Lagrangian of the Standard Model: mass terms

Dirac mass terms in the Standard Model with the Higgs doublet

$$\mathcal{L} = -f_e \left(\overline{\nu_e}, \bar{e}\right)_L \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} e_R - f_u \left(\bar{u}, \bar{d}\right)_L \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}^C u_R - f_d \left(\bar{u}, \bar{d}\right)_L \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} d_R + \ldots + h.c.$$

No neutrino mass terms, since there exist no right-handed neutrinos ν_R in the SM !

Spontaneous symmetry breaking (loose 3 d.o.f. to give W^+, W^- and Z^0 mass):

$$\begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

Fermion mass terms:

$$\mathcal{L} = -\underbrace{\frac{f_e \cdot v}{\sqrt{2}}}_{:= m_e} \overline{e_L}\, e_R - \underbrace{\frac{f_u \cdot v}{\sqrt{2}}}_{:= m_u} \overline{u_L}\, u_R - \underbrace{\frac{f_d \cdot v}{\sqrt{2}}}_{:= m_d} \overline{d_L}\, d_R + \ldots + h.c.$$

General: Dirac mass terms for fermions in the standard model:

$$\mathcal{L} = m_D \left(\overline{\Psi_L}\Psi_R + \overline{\Psi_R}\Psi_L\right) + \ldots$$

Neutrino sources and energy spectra

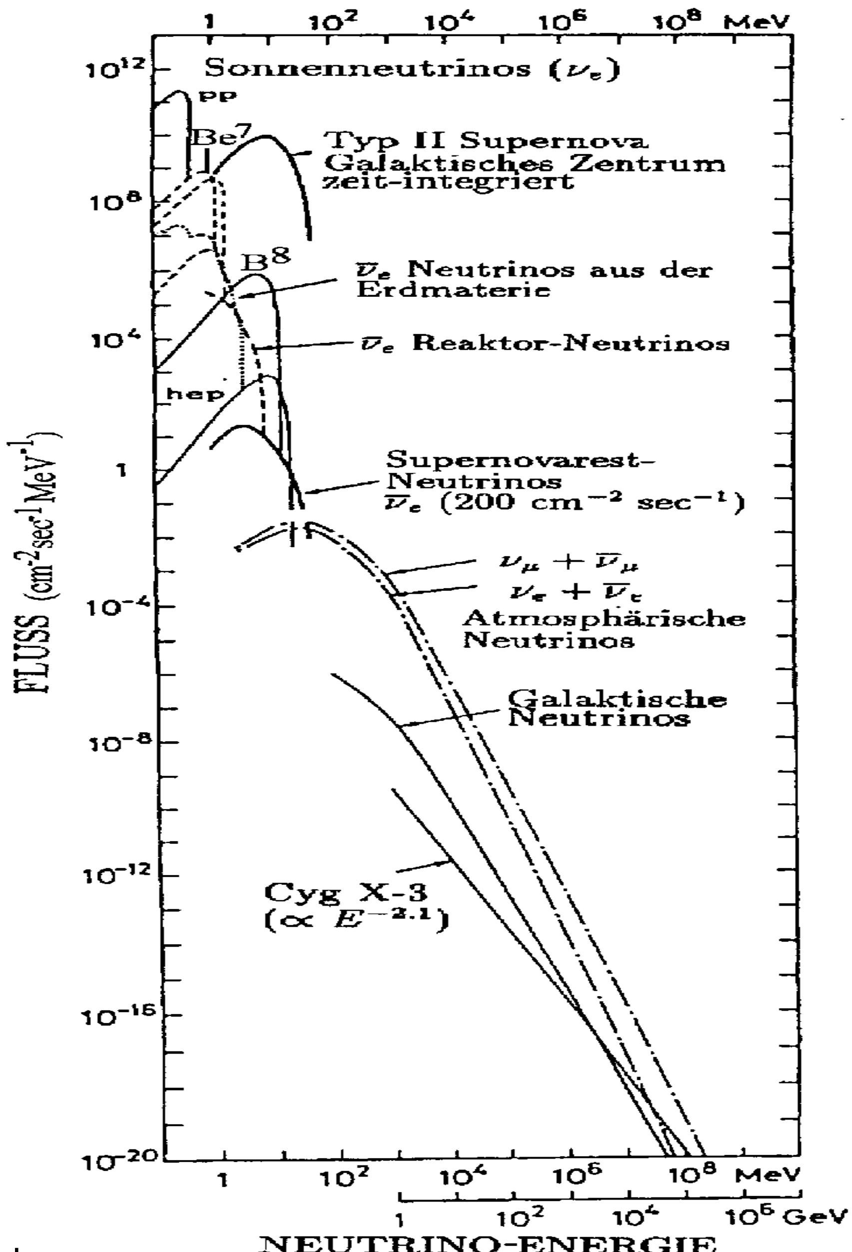


figure: Schmitz: Neutrinophysics, Teubner

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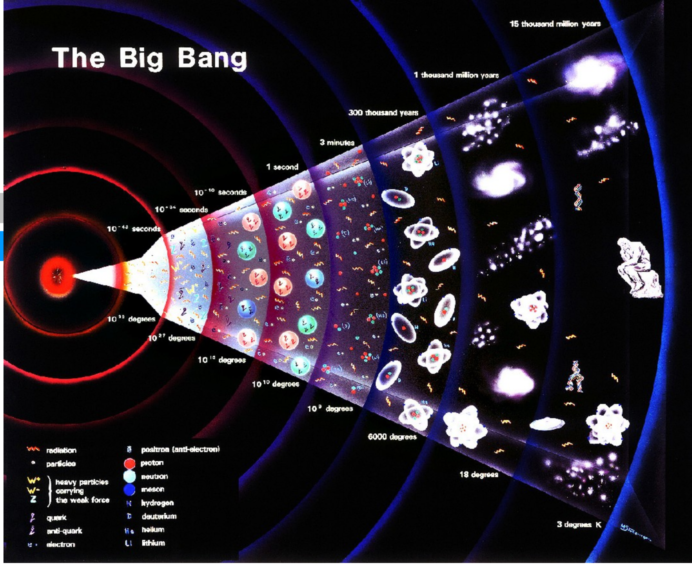
Relic neutrinos (very brief)



- In the early universe, neutrinos, electrons/positrons and photons are in thermal equilibrium:
  equal temperatures $T_\nu = T_\gamma$
  and equal densities $n_\nu = n_\gamma = 1.6 \cdot 10^9\, n_B$
- At $T \approx 1$ MeV, the neutrinos decouple, since the interaction rate gets too slow: $\Gamma < H$
  $\Rightarrow$ further on same temperatures ($T_\nu = T_\gamma$) and same densities ($n_\nu = n_\gamma$)
- At $T \approx 0.5$ MeV, the electrons and positrons annihilate into photons
  $\Rightarrow$ increase of photon density and adiabatic re-heating of photons
  Conservation of entropy and correct counting of degrees of freedom yields

$$T_\gamma = (11/4)^{1/3}\, T_\nu$$

- Today: cosmic microwave background (CMB):
  $T_\gamma = 2.725$ K $n_\gamma = 411\ \mathrm{cm}^{-3}$ (Planck`s law)
  and cosmic neutrino background („relic neutrinos“):
  $T_\gamma = 1.9$ K $n_\nu = 336\ \mathrm{cm}^{-3}$ (all flavours, ν and $\bar{\nu}$)
  (Calculation were done for massless neutrinos, but density n_ν is correct for $m_\nu \neq 0$)
  Comparison: $m_\nu = 0.7$ eV $\Rightarrow$ $\rho_\nu \approx \rho_B$

Summary of neutrinos in the Standard Model of particle physics

- ν's are left-handed,
  charged fermions in CC reactions (W exchange) are also left-handed
  charged fermion coupling to the Z^0 is more complicated
  (since the Z^0 is a superposition of the „hypercharge photon B" and the W^3)
- ν's are massless,
  since there is no right-handed neutrino to construct a „Dirac mass term"

$$\mathcal{L} = - m \overline{\Psi}_L \Psi_R - m \overline{\Psi}_R \Psi_L$$

- ν's have very small cross section (due to very heavy W and Z)
- If there are no thresholds, ν cross section are proportional to ν lab energy E_ν
- There are 336 relic ν's per cm^3 in the universe, a billion times more than atoms