Neutrino Physics: an Introduction

Lecture 1: Detection and basic properties

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Lecture 1: Neutrino detection and basic properties

- Unique properties
- Discovery of neutrino flavours
- Measuring mass, helicity, interactions

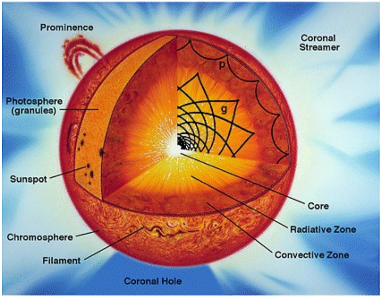
Lecture 2: Neutrino mixing and oscillations

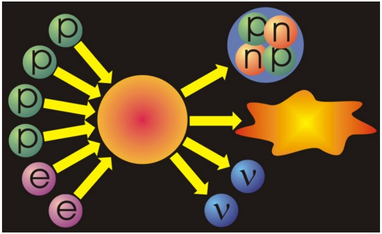
- Solar and atmospheric puzzles and solutions
- The three-neutrino mixing picture
- How to measure neutrino mixing parameters

Lecture 3: Neutrinos in astrophysics and cosmology

- Low-energy (meV) cosmological neutrinos
- Medium-energy (MeV) supernova neutrinos
- High-energy ($>$ TeV) astrophysical neutrinos

How does the Sun shine ?





- Nuclear fusion reactions: effectively

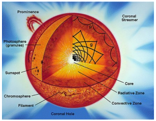
$$4\ {}^1_1\mathrm{H} + 2e^- \rightarrow {}^4_2\,\mathrm{He} + \mathrm{light} + 2\nu_e$$

- Neutrinos needed to conserve energy, momentum, angular momentum

Neutrinos essential for the Sun to shine !!

Davis-Koshiba Nobel prize 2002

Neutrinos from the Sun: some interesting facts



A very very large number of neutrinos

About hundred trillion through our body per second

Hundred trillion = 100 000 000 000 000

Why do we not notice them ?

Even during night !

If sunlight cannot reach, how do neutrinos ?

Seem to come directly from the core of the Sun

Sunlight comes from the surface...

What are the reasons for these confusing facts ?

Three questions, the same answer

- Why did the *roti* burn ?
- Why did the betel leaves *(paan)* rot ?
- Why could the horse not run ?

Because they were not moved !

Three questions about neutrinos

Pauli Dirac

- Why do we not notice neutrinos passing through us?
- Why do neutrinos from the Sun reach us during night ?
- Why can we see “inside” the sun with neutrinos ?

Because neutrinos interact extremely weakly !

The most weakly interacting particles

Stopping radiation with lead shielding

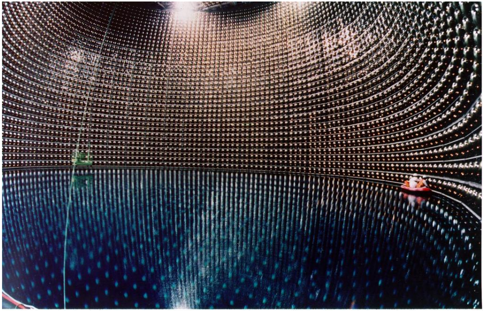
- Stopping α, β, γ radiation: 50 cm
- Stopping neutrinos from the Sun: light years of lead !

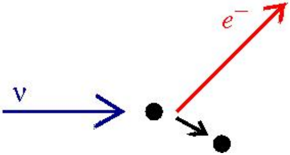
Answers to the three questions

- Why do we not notice neutrinos passing through us?
  Neutrinos pass through our bodies without interacting
- Why do neutrinos from the Sun reach us during night ?
  Neutrinos pass through the Earth without interacting
- Why can we see “inside” the sun with neutrinos ?
  Neutrinos pass through the Sun without interacting

How do we see the neutrinos then ?

SuperKamiokande: 50 000 000 litres of water





A very rare observation

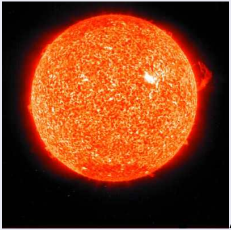
- About 10^{25} neutrinos pass through SK every day.
- About 5–10 neutrinos interact in SK every day.

Recipe for observing neutrinos

- Build very large detectors
- Wait for a very long time

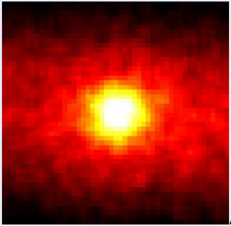
How does the Sun look in neutrinos ?

Sun in photons: a few million years ago



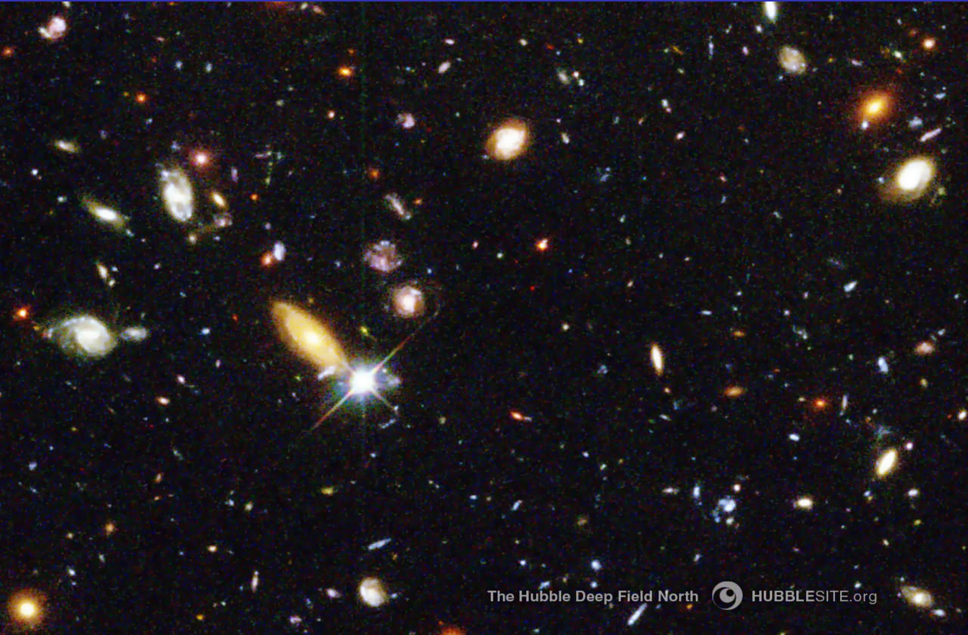
Angular size $\sim 1^\circ$

Sun in neutrinos: 8 minutes ago

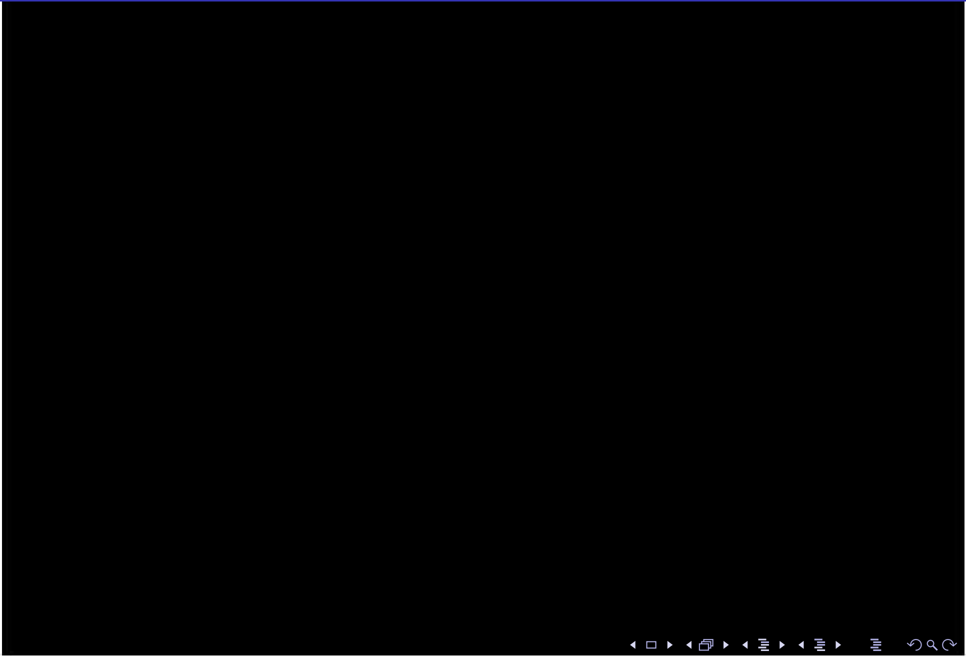


Angular size $\sim 20^\circ$

A view from the Hubble telescope



The world without neutrinos



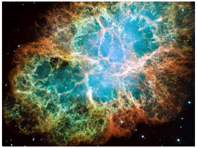
The world without neutrinos

Role of neutrinos in creating atoms

Neutrinos helped create the matter-antimatter asymmetry, without which, no atoms, no stars, no galaxies

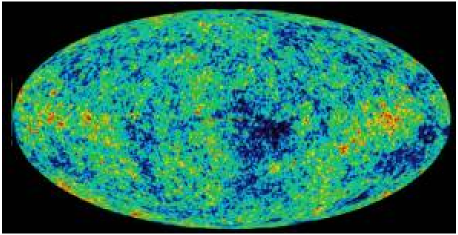
Role of neutrinos in creating the Earth

- Earth has elements heavier than iron, which cannot be created inside the Sun, or in any ordinary star
- This can happen only inside an exploding star (supernova)! (Or a kilonova like the one recently observed)
- A supernova must have exploded bilions of years ago whose fragments formed the solar system



Supernovae explode because ...
neutrinos push the shock wave from inside !

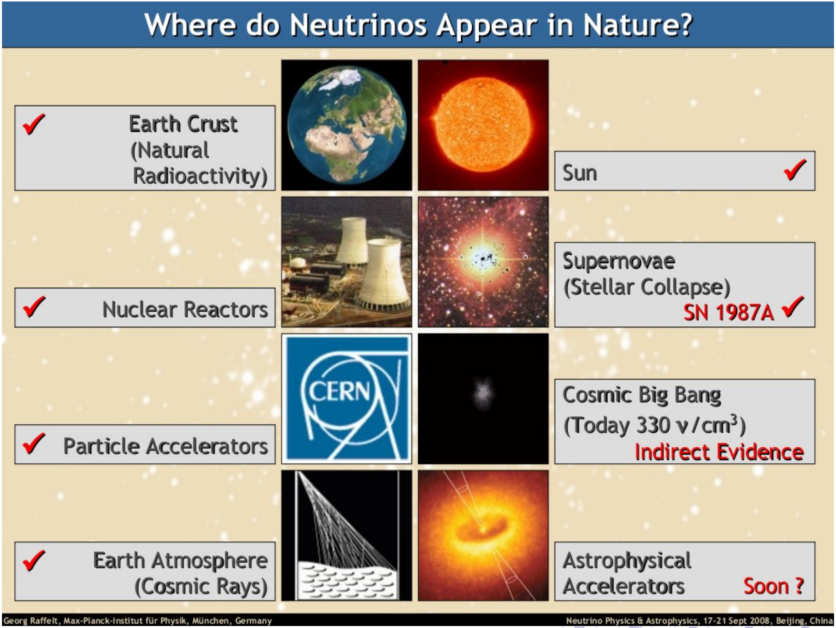
The second-most abundant particles in the universe



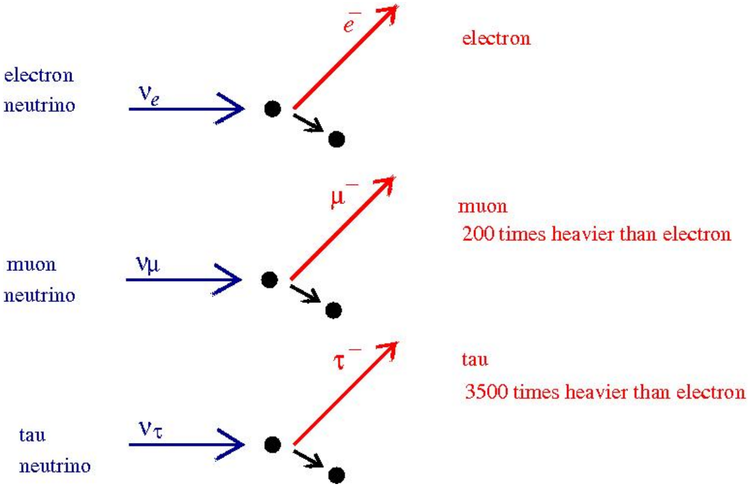
- Cosmic microwave background: 400 photons/ cm^3
  Temperature: $\sim$ 3 K
- Cosmic neutrino background: 300 neutrinos / cm^3
  Temperature: $\sim$ 2 K

Even empty space between galaxies is full of neutrinos !

Neutrinos everywhere

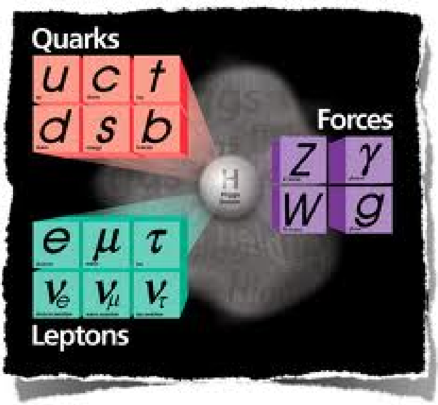


Three kinds of neutrinos: ν_e ν_μ ν_τ



Positive particles coming out $\Rightarrow$ antineutrinos

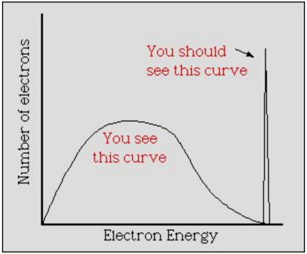
The Standard Model of Particle Physics



- 3 neutrinos: ν_e, ν_μ, ν_τ
- chargeless
- spin 1/2
- almost massless (at least a million times lighter than electrons)
- only weak interactions

The beta decay mystery: 1932

- Nuclear beta decay: $X \rightarrow Y + e^-$
- Conservation of energy and momentum $\Rightarrow$ Electrons have a fixed energy.
- But:



- Energy-momentum conservation in grave danger !!

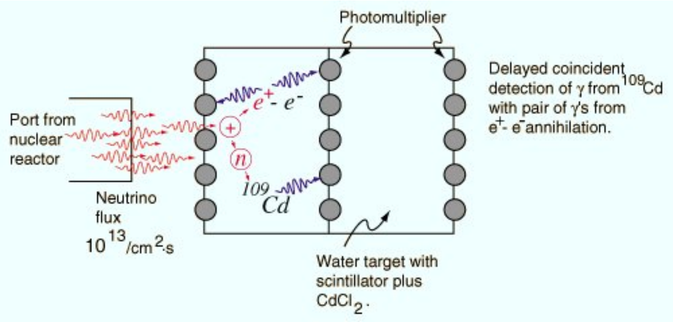
A reluctant solution (Pauli): postulate a new particle

Discovery of electron neutrino: 1956

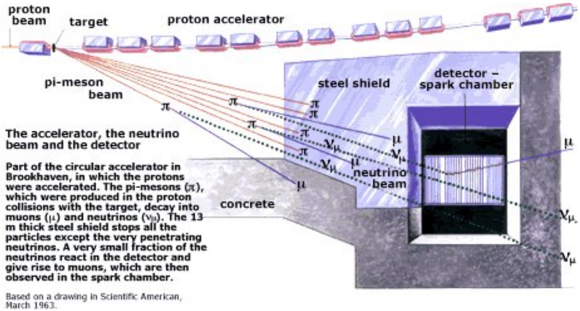
The million-dollar particle

- Reactor neutrinos: $\bar{\nu}_e + p \to n + e^+$
- $e^+ + e^- \to \gamma + \gamma$ (0.5 MeV each)
- $n + {}^{108}\mathrm{Cd} \to {}^{109}\mathrm{Cd}^* \to {}^{109}\mathrm{Cd} + \gamma$ (delayed)

Reines-Cowan: Nobel prize 1995



The “Who ordered muon neutrino ?” mystery: 1962



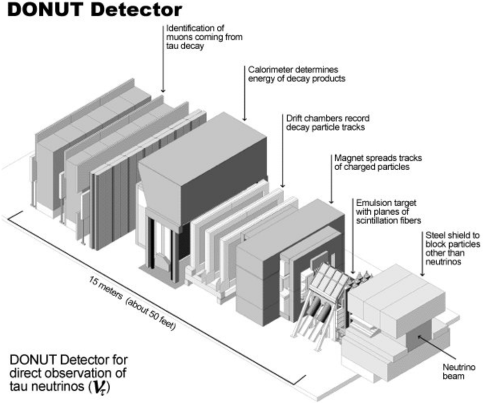
Muon neutrino: an unexpected discovery

- Neutrinos from pion decay: $\pi^- \to \mu^- + \bar{\nu}$
- Expected: $\bar{\nu} + N \to N' + e^+$??
- Observed: always a muon, never an electron/positron
- This must be a new neutrino, not $\bar{\nu}_e$, but $\bar{\nu}_\mu$

Steinberger-Schwartz-Lederman Nobel prize 1988

The expected tau discovery

DONUT@Fermilab, 2000: emulsion+calorimeter



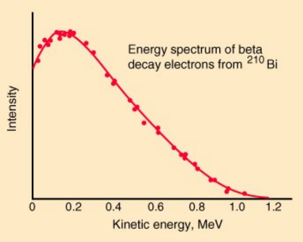
Combination of many detectors needed

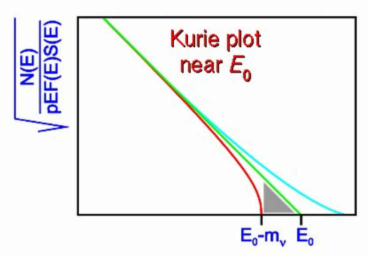
- $\nu_\tau \to \tau$, whose decays need to be observed
- Emulsion + Drift chamber + Calorimeter + Muon chamber

Direct mass measurement

How do you hold a moonbeam in your hand ?

Nuclear beta decay





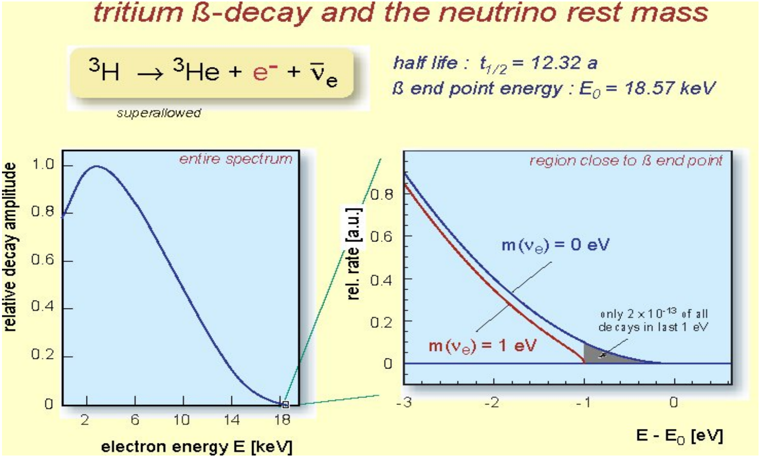
$$\frac{d\Gamma}{dE_e} \propto p_e E_e p_\nu E_\nu = p_e E_e (E_0 - E_e)\sqrt{(E_0 - E_e)^2 - m_\nu^2}$$

Kurie plot:

$$\left(\frac{d\Gamma/dE_e}{p_e E_e}\right)^{1/2} \propto \left[(E_0 - E_e)\sqrt{(E_0 - E_e)^2 - m_\nu^2}\right]^{1/2}$$

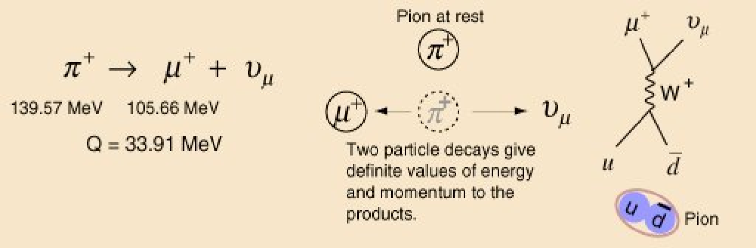
Straight line for a massless neutrino !

Tritium beta decay experiment



- Mainz exeriment: $m_{\nu_e} < 2.2$ eV (95% C.L.)
- Troitsk experiment: $m_{\nu_e} < 2.05$ eV (95% C.L.)
- Next generation expt: KATRIN (reach 0.2 eV)

Muon neutrino mass



- Mass of ν_μ decides the energy of μ^+.

$$E_\mu = \frac{m_\pi^2 + m_\mu^2 - m_\nu^2}{2m_\pi}$$

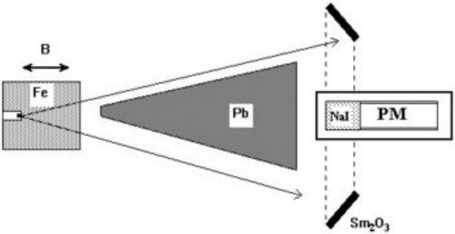
- Current limit: $m_{\nu_\mu} < 170$ keV

Helicity

- Spin component along the direction of motion
- If detection itself is so hard, measuring spin would be even harder !
- Need clever experiment, where neutrino does not need to be observed !

Goldhaber experiment

${}_{63}\mathrm{Eu}^{132}$ decay :



$$\begin{array}{cccccc} \nu_e & \longleftarrow \mathrm{Eu} + e^- \longrightarrow & \mathrm{Sm}^* & \longrightarrow \gamma_1 & \mathrm{Sm}^* \rightarrow \mathrm{Sm} + \gamma_2 \\ \Leftarrow \frac{1}{2} & \Rightarrow \frac{1}{2} & \Rightarrow 1 & \Rightarrow 1 & \times \\ \Rightarrow \frac{1}{2} & \Leftarrow \frac{1}{2} & \Leftarrow 1 & \Leftarrow 1 & \surd \end{array}$$

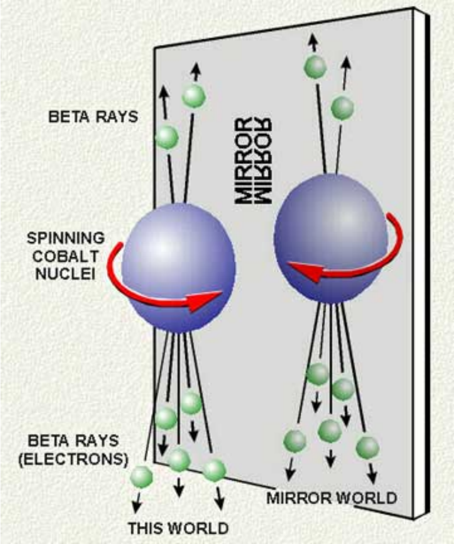
Goldhaber et al, PRL 1957
http://qd.typepad.com/6/2005/01/spinning_neutri.html

Implications of Goldhaber's experiment

- Neutrinos only have negative helicity
- Maximal violation of mirror symmetry (Parity)

Cobalt decay experiment

(Wu et al)



Pion decay experiment

(Garwin, Lederman, Weinrich) $\pi^- \rightarrow \mu^- \rightarrow e^-$

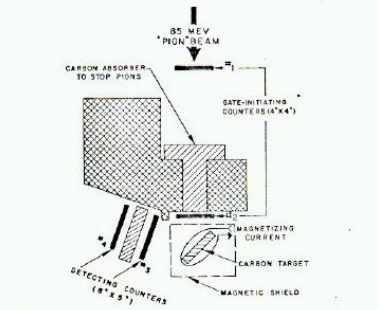


Fig. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

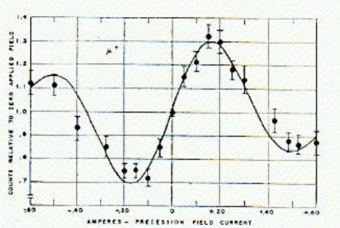
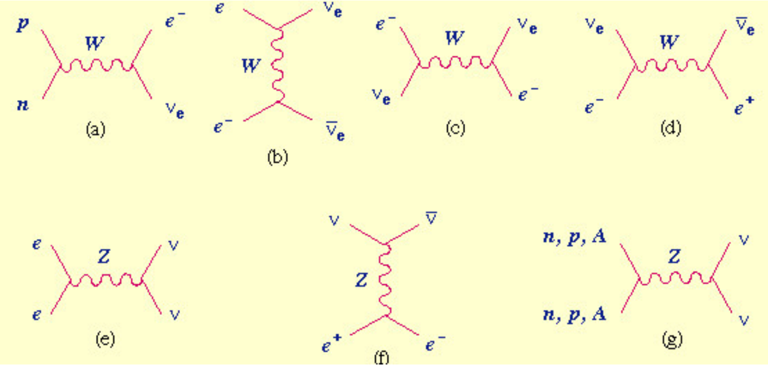


Fig. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

Neutrino Interactions

- Only weak interctions (with W and Z bosons)

- Interactions with matter through exchange of W and Z



Cross section calculation

ν interactions in the SM:

CC / NC

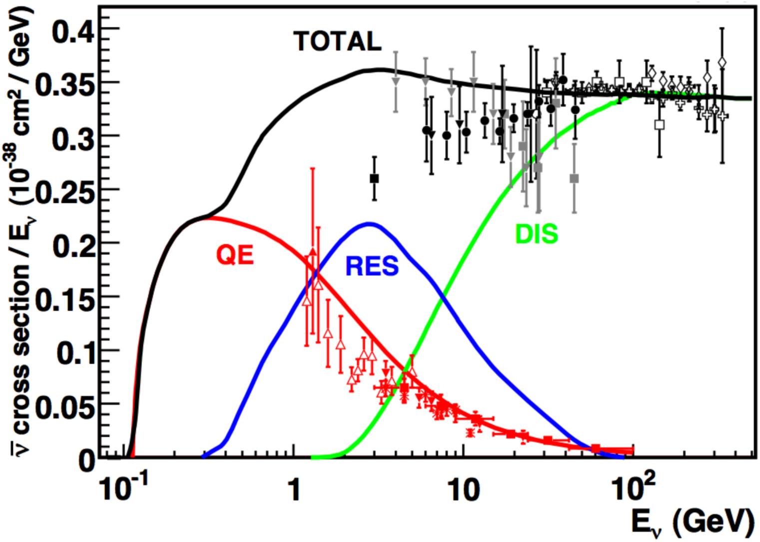
with quarks / leptons

Cross sections:
http://cupp.oulu.fi/neutrino/nd-cross.html

Cross section estimation at high energies:

$$\sigma \sim G_F^2 s \sim 10^{-44} \frac{E_\nu}{GeV} \ m^2 \quad \text{(for electrons)}$$

Quasi-elastic and deep inelastic scattering



Cross section in a detector: various processes

Where are we now (at the end of Lecture 1)

- Neutrinos interact extremely weakly
- Neutrino flavours: definitions and discoveries
- Neutrino mass < eV, Neutrino helicity: always negative !