Outline: Neutrino

Lecturer: Hans-Jürgen Wollersheim

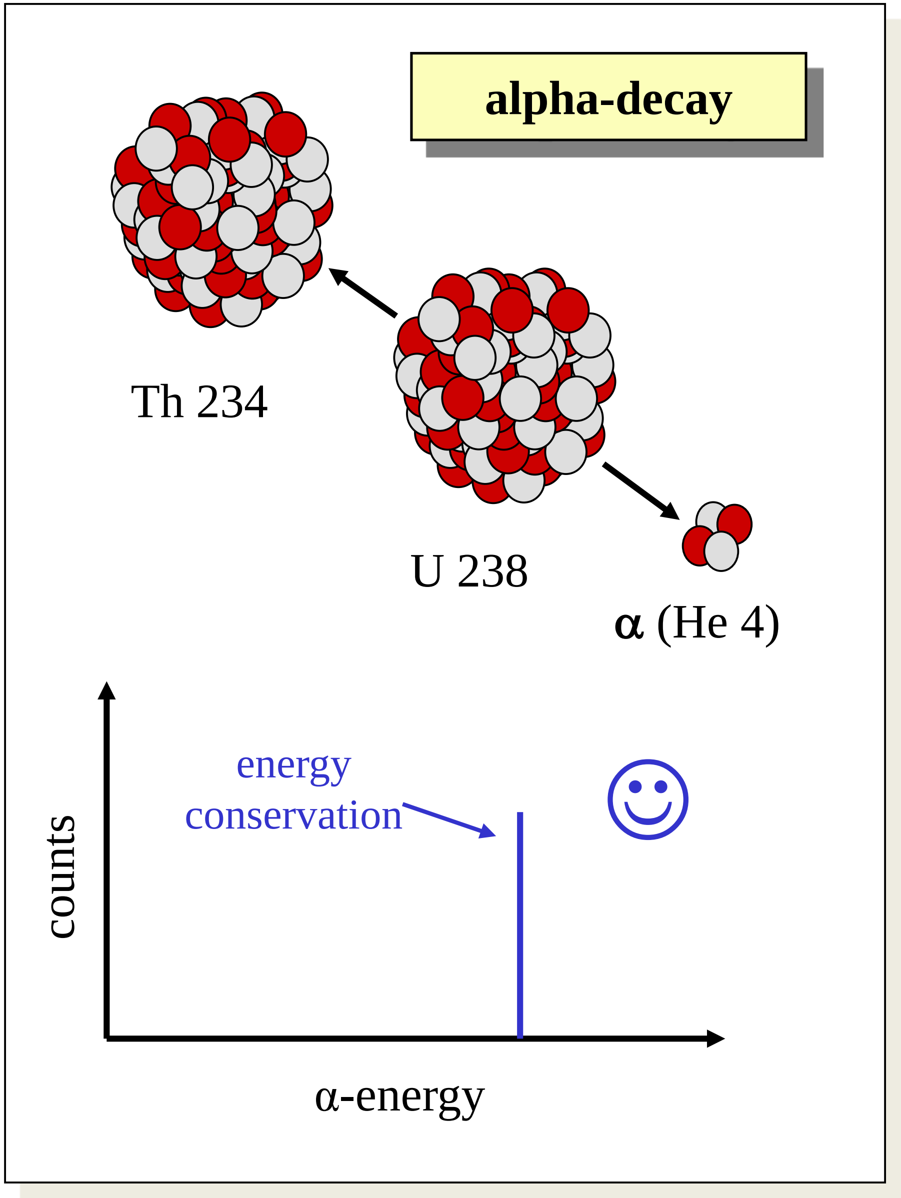
e-mail: h.j.wollersheim@gsi.de

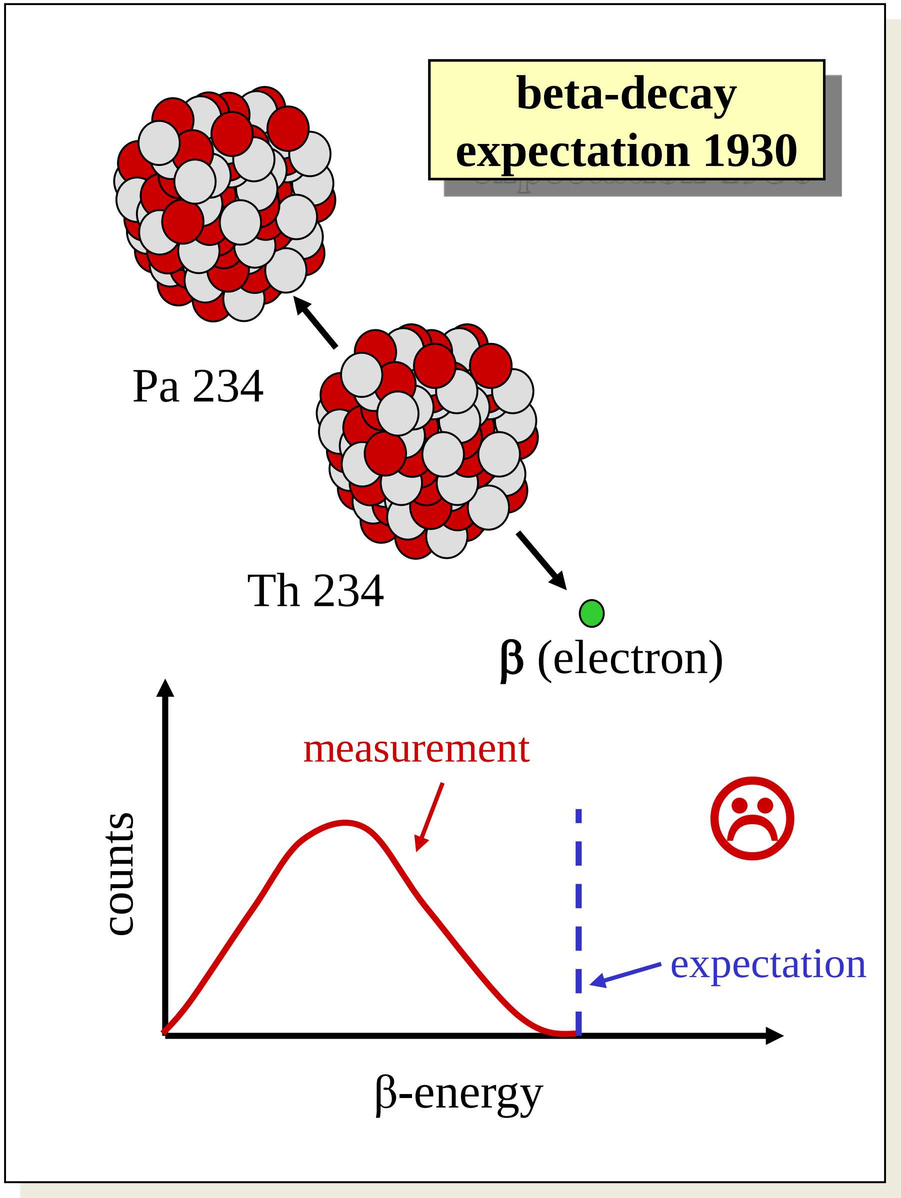
web-page: https://web-docs.gsi.de/~wolle/ and click on

Kernphysik Skript (H.J. Wollersheim)

1. β-decay and the proposed neutrino
2. neutrino's from the sun
3. neutrino oscillations
4. Dirac or Majorana fermions

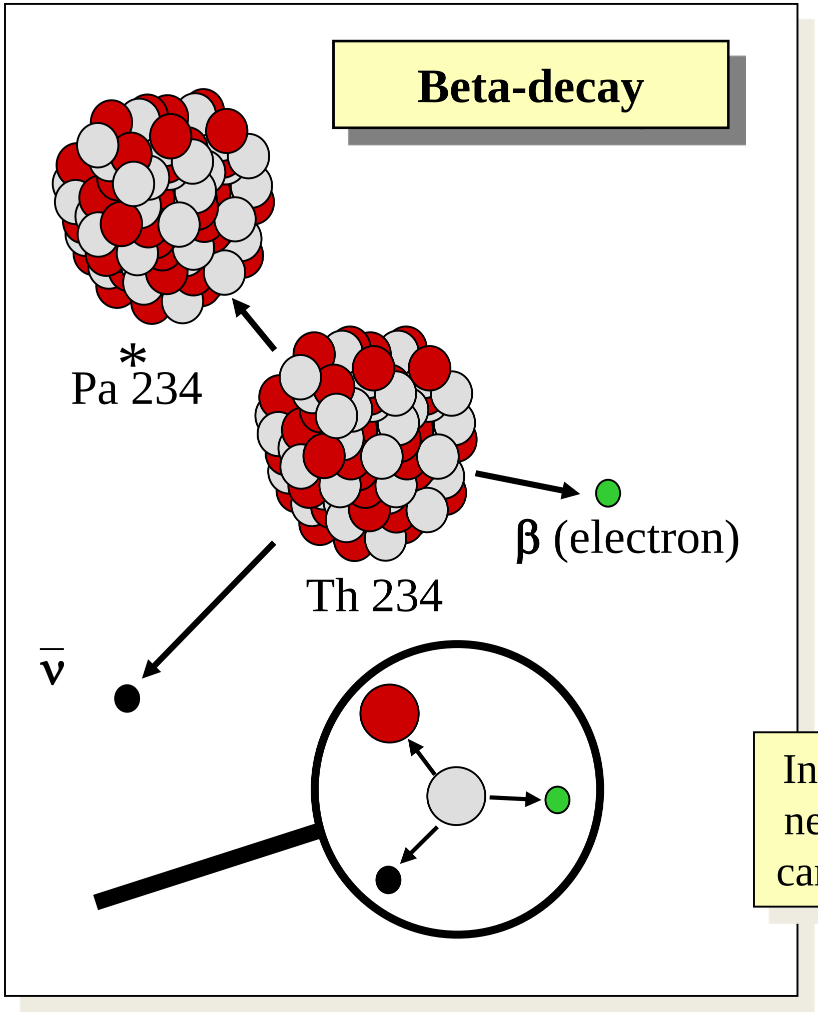
1930: Energy conservation violated in β-decay





The new particle proposed by Pauli

Wolfgang Pauli



Leptonen			
Charge	–1	Charge	0
Electron	e	e-Neutrino	ν_e
Myon	μ	μ-Neutrino	ν_μ
Tauon	τ	τ-Neutrino	ν_τ

In addition to an electron a light neutral particle is created which carries away the missing energy!

„Today I have done something, what one should not do in theoretical physics. I have explained something, what is not understood, by something, which can not be observed!"

Neutrino detection

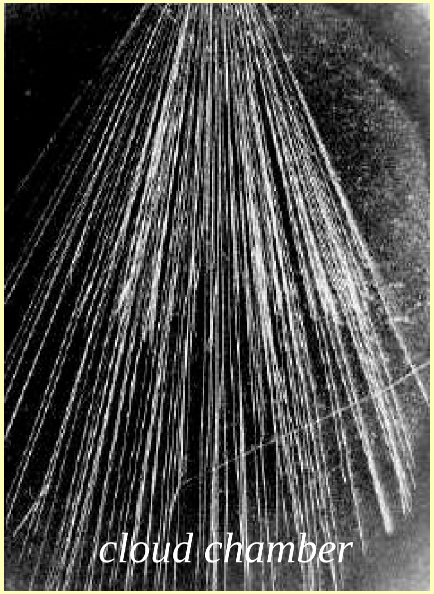
- Detection of particles:

  Interaction of particles with matter (detector)

- Interaction with matter depends strongly on the particle:

  Charge particles: Ionization of matter

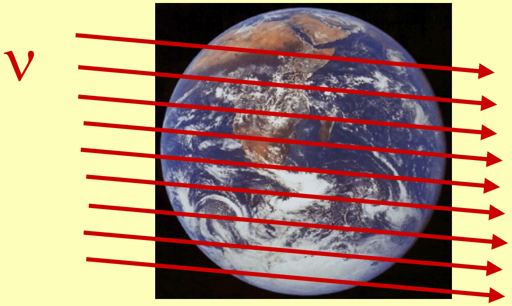
  Photons: Energy transfer to charged particles
  Neutrons: Nuclear reactions yield charge particles



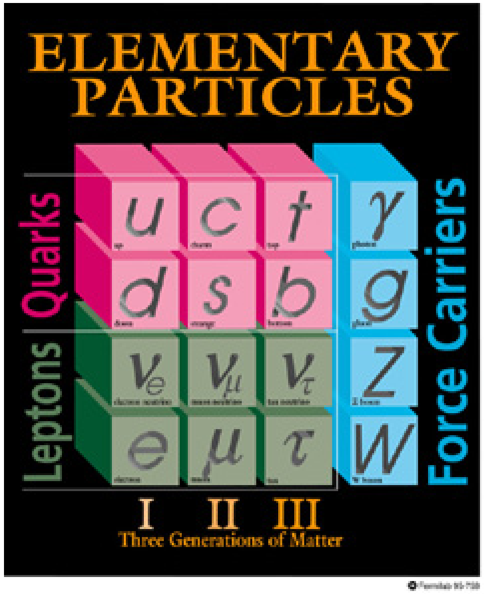
- Neutrinos interact very weakly:

  Only one out of 100 billions neutrinos from the β-decay will be recognized by the earth.

  Calculated 1934: „Hopeless“

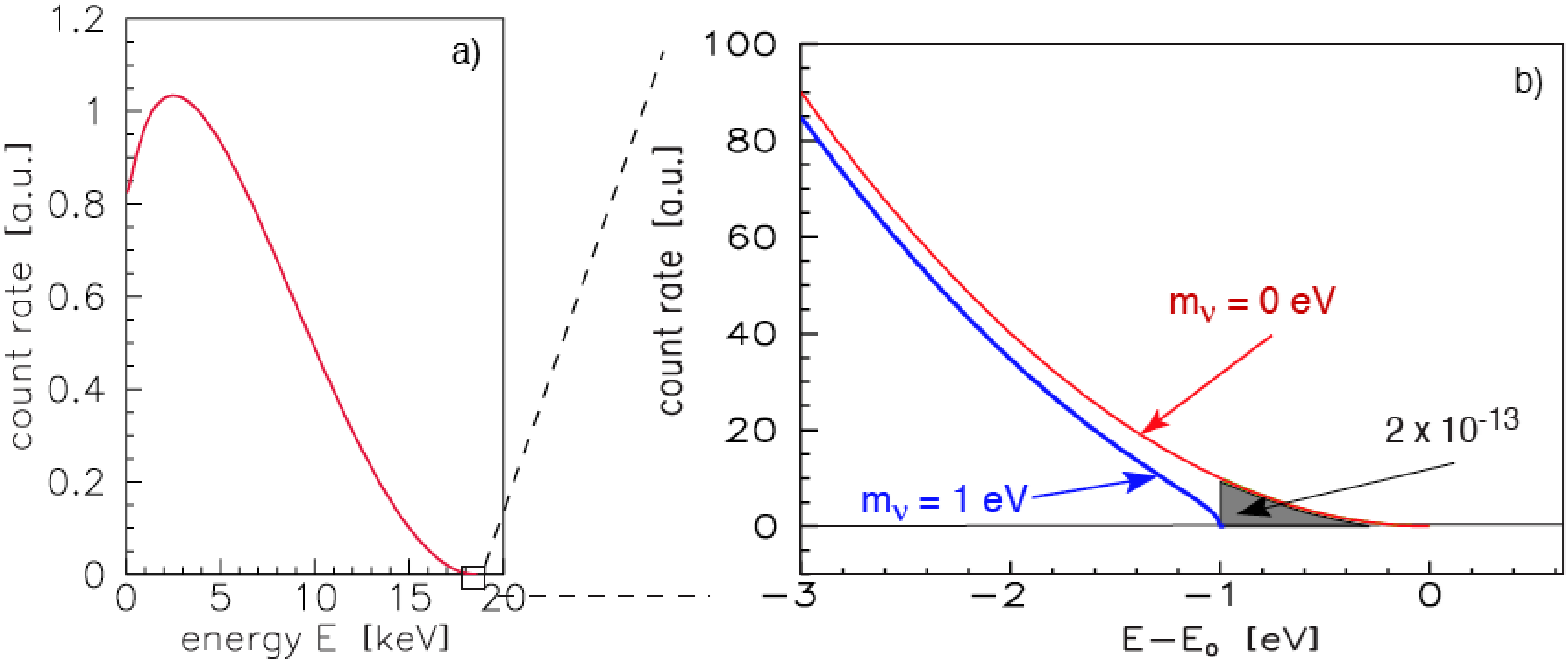


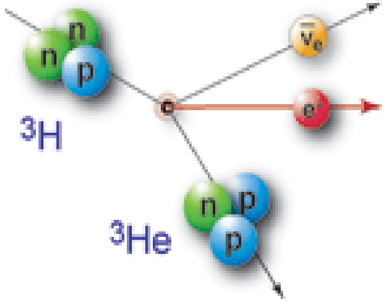
Neutrino, the story



- Proposed by W. Pauli in 1930
- Reactor ν_e observed,1953
- $\nu_e \neq \nu_\mu$, 1960-64
- Electro-weak theory GWS
- Neutral current discovered, 1973
- Z, W observed at LEP, 1983
- Z width ⇒ 3 ν families
- ν_τ,
- Standard Model almost complete

Kinematical experiments





$$\frac{dN}{dE_e} = CF(Z,E_e)p_e(E_e + m_e c^2)(E_0 - E_e)\sum_j |U_{ej}|^2 \boxed{[(E_0 - E_e)^2 - m_{\nu_j}^2]^{1/2}}$$

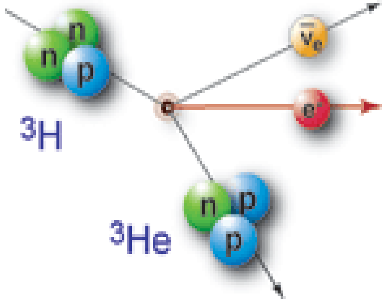
Kinematical experiments

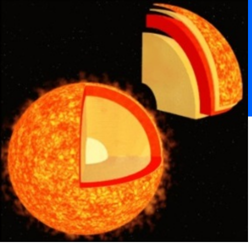
Challenges:

- Small rate at the tail ⇒ low Q_β
- Energy resolution ~ m_ν ⇒ non-traditional detectors
- Effect is at the scale of atomic energy (H line 13.6 eV) ⇒ enormous effort to control systematic error

- ^{3}H 18 keV β-decay (Troitsk, Maiz, Katrin) ⇒ Use of MAC-E filter

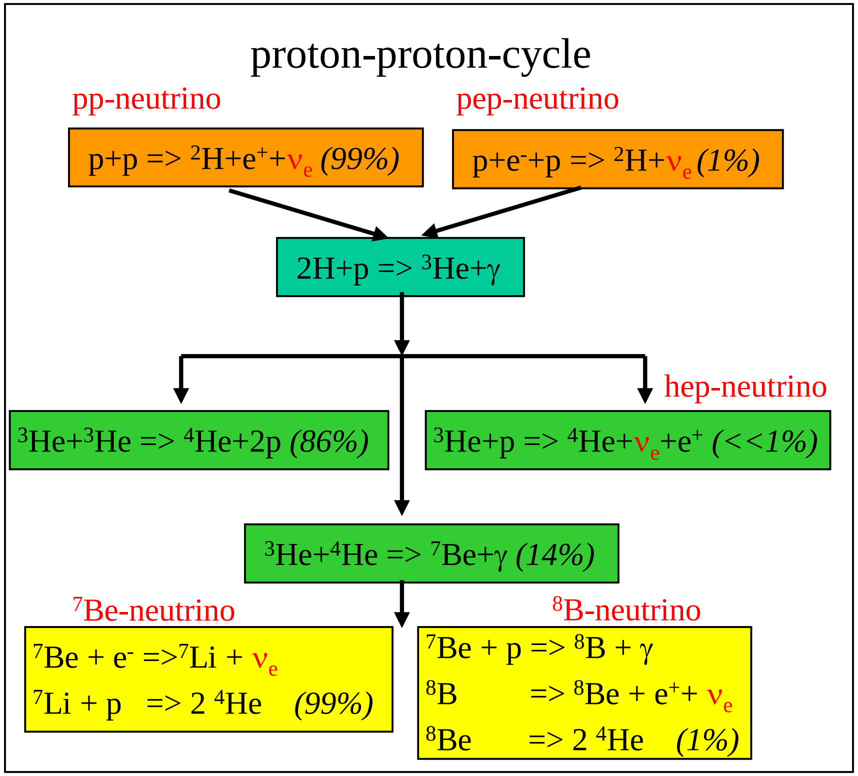
- ^{187}Re 2.47 keV β-decay (MARE) ⇒ Use of cryogenic bolometer (see CUORE experiment for bolometer detector)





Neutrinos from the sun

$$4\,\text{protons} \rightarrow \text{He-nucleus} + 2e^{+} + 2\nu + 26MeV$$



proton-proton-cycle

pp-neutrino

$p+p \Rightarrow {}^2H+e^+ + \nu_e$ *(99%)*

pep-neutrino

$p+e^-+p \Rightarrow {}^2H+\nu_e$ *(1%)*

$2H+p \Rightarrow {}^3He+\gamma$

${}^3He+{}^3He \Rightarrow {}^4He+2p$ *(86%)*

hep-neutrino

${}^3He+p \Rightarrow {}^4He+\nu_e+e^+$ *(<<1%)*

${}^3He+{}^4He \Rightarrow {}^7Be+\gamma$ *(14%)*

^{7}Be-neutrino

${}^7Be + e^- \Rightarrow {}^7Li + \nu_e$

${}^7Li + p \Rightarrow 2\,{}^4He$ *(99%)*

^{8}B-neutrino

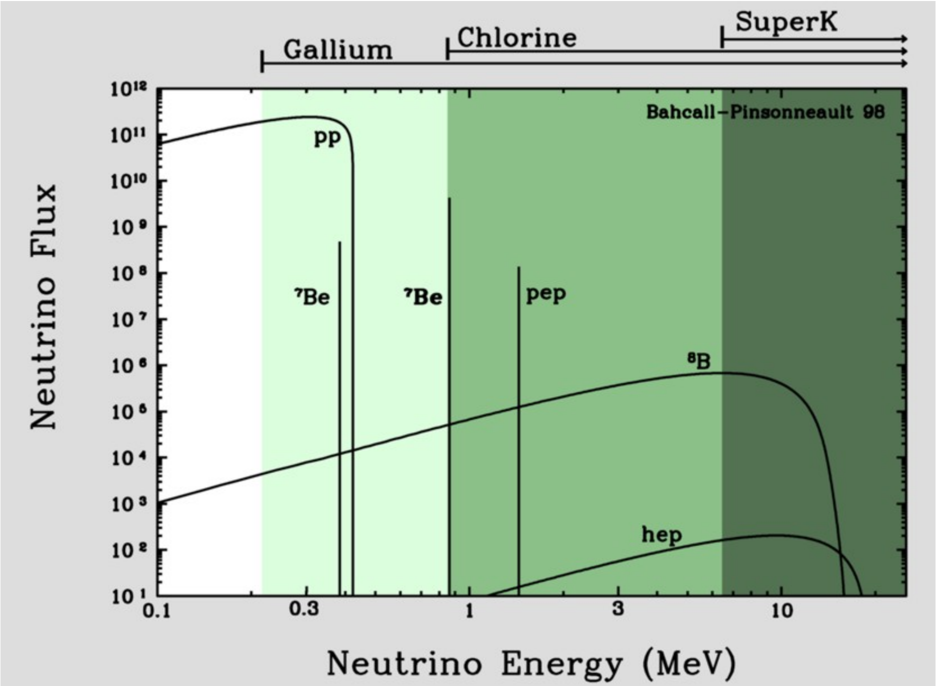
${}^7Be + p \Rightarrow {}^8B + \gamma$

${}^8B \Rightarrow {}^8Be + e^+ + \nu_e$

${}^8Be \Rightarrow 2\,{}^4He$ *(1%)*

- Known: total emitted energy
- Known: energy per fusion process

➢ number of created neutrinos per sec!
on earth: 66 billions ν per $(cm^2 \cdot s^1)$



Solar neutrino energy spectrum

Interaction of Neutrinos

- $\nu_e + n \rightarrow p + e^-$
- $\bar{\nu}_e + p \rightarrow n + e^+$ (discovery of the neutrino)
- $\nu_\mu + n \rightarrow p + \mu^-;\ \ \nu_\tau + n \rightarrow p + \tau^-$
- $\bar{\nu}_\mu + p \rightarrow n + \mu^+;\ \ \bar{\nu}_\tau + p \rightarrow n + \tau^+$

- Small cross section for MeV neutrinos:

$$\sigma(\nu_e N) = \frac{4}{\pi} \cdot 10^{-10} \left\{\frac{\hbar p}{\left(m_p c\right)^2}\right\}^2 = 1.6 \cdot 10^{-44} cm^2 \quad for\ 0.5\ MeV$$

- Rate of solar neutrinos interacting in the Earth:

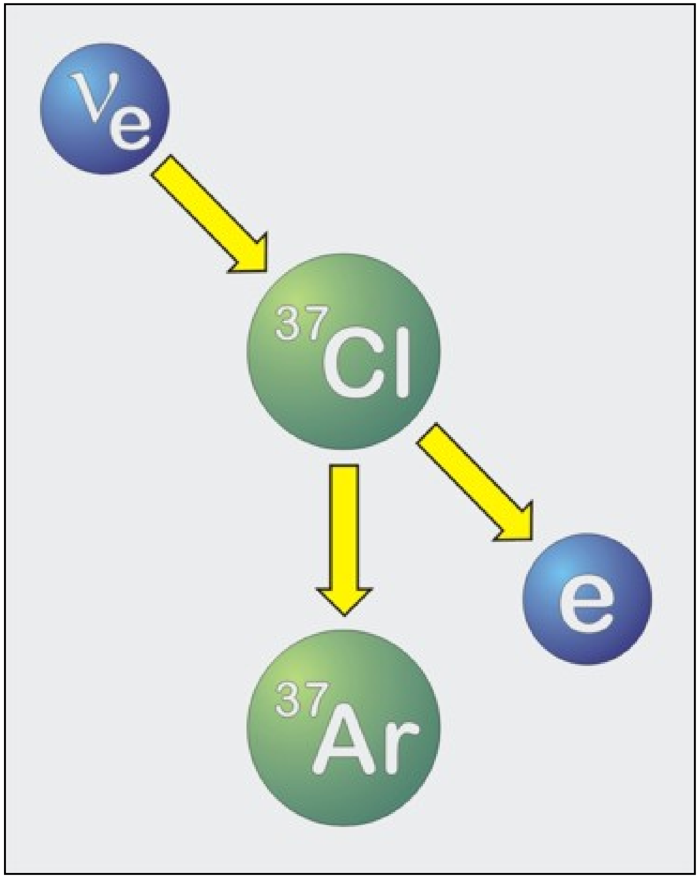
$$N \cdot \sigma \cdot d \cdot \rho \cdot flux = 6.022 \cdot 10^{23} \cdot 1.6 \cdot 10^{-44} cm^2 \cdot 1.2 \cdot 10^9 cm \cdot 5.5 \frac{g}{cm^3} \cdot 6.7 \cdot 10^{10} cm^{-2} s^{-1} = 4 cm^{-2} s^{-1}$$

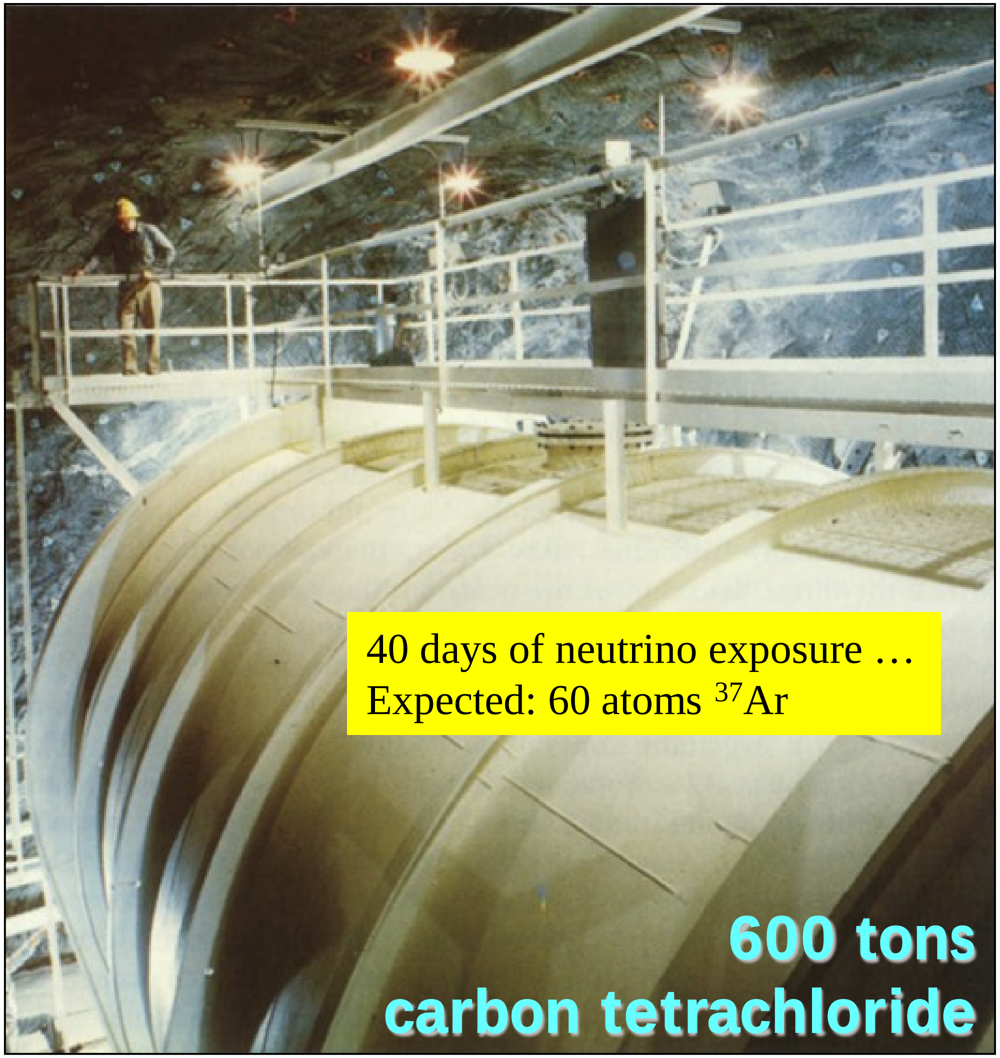
- For high energies (GeV-range):

$$\sigma\left(\nu_\mu N\right) = 0.67 \cdot 10^{-38} \cdot E_\nu [GeV] \quad cm^2/nucleon$$

First measurements of the solar neutrinos

Inverse beta-decay („neutrino-capture”)



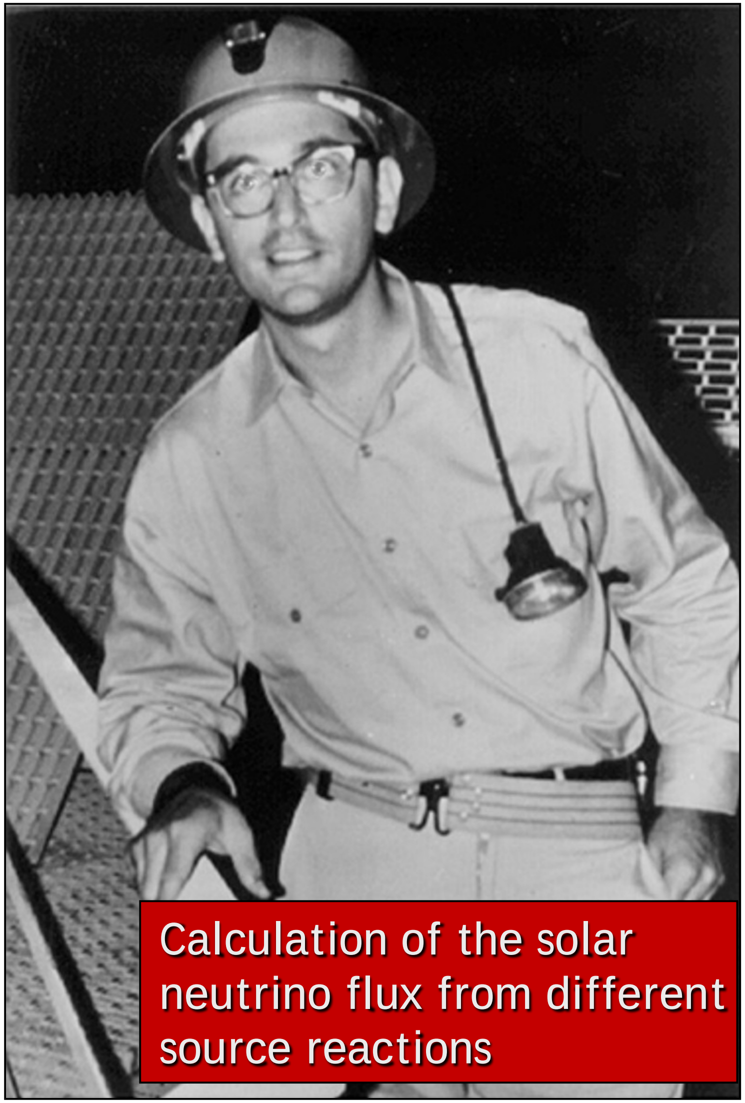


40 days of neutrino exposure …
Expected: 60 atoms ^{37}Ar

600 tons carbon tetrachloride

Homestake Solar Neutrino Observatory (1967–2002)

Problem of the “missing” solar neutrinos

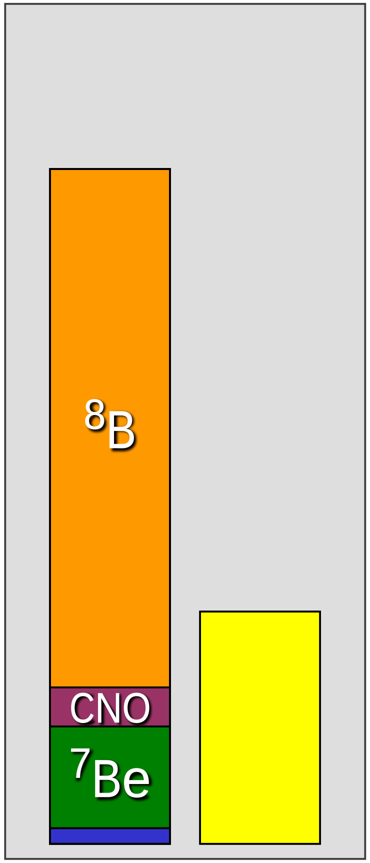


Calculation of the solar neutrino flux from different source reactions

John Bahcall
1934 – 2005

Homestake

Chlorine

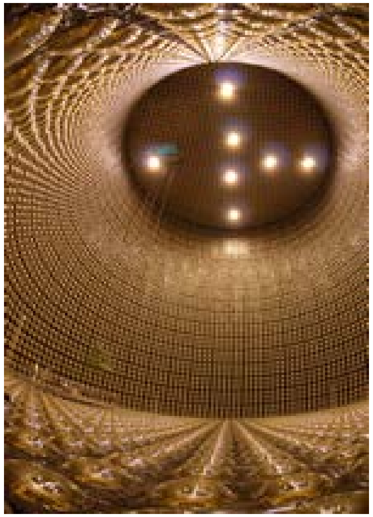


Measurements (1970 – 1995)

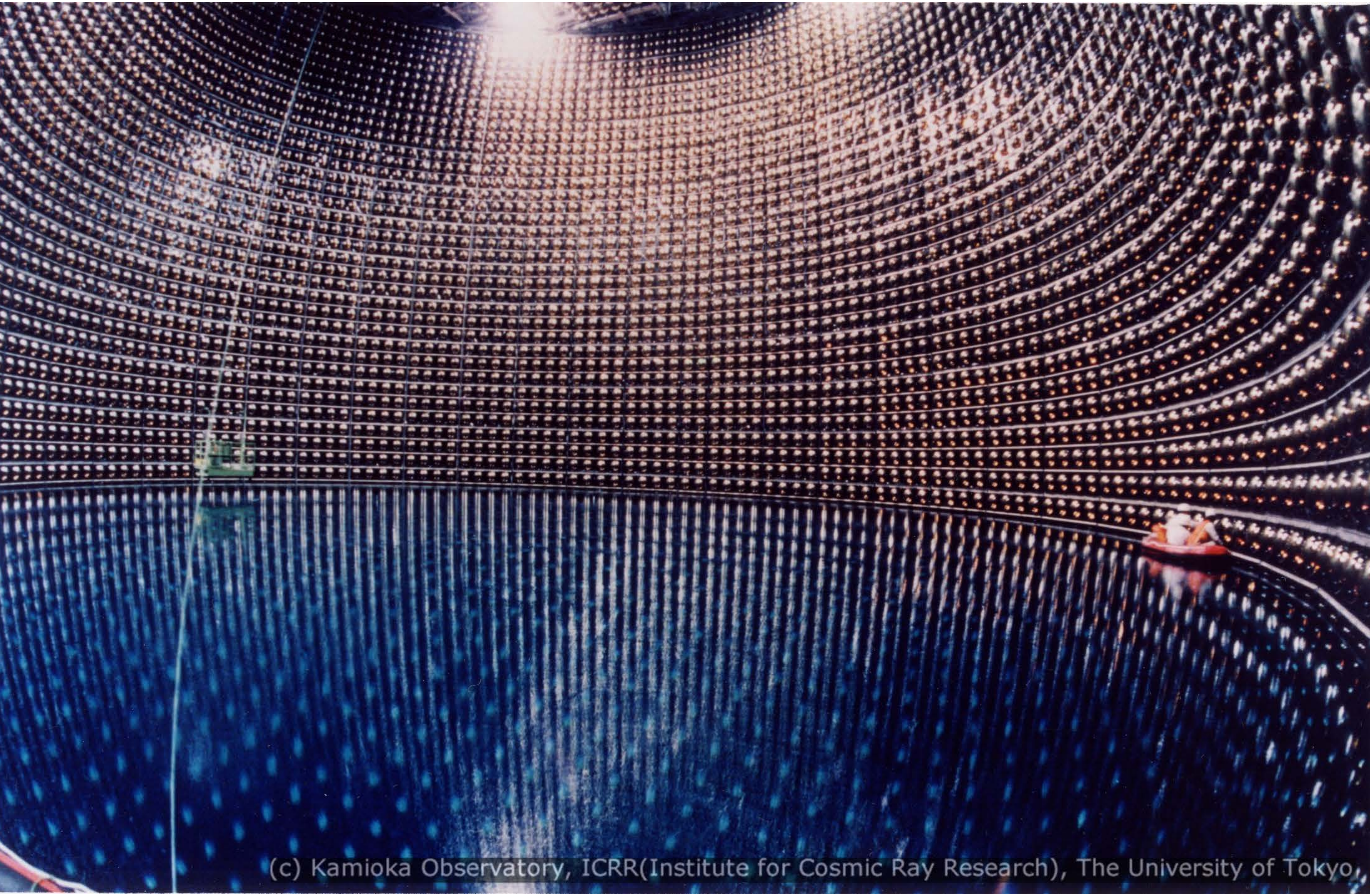
Raymond Davis Jr.
1914 – 2006

Super Kamiokande – the Detector

- 40 m water tank
- filled with 50 ktons pure water
- largest water Cherenkov detector in the world!
- >11,000 photomultipliers (PMTs) to detect light
- PMTs + electrical connections waterproof



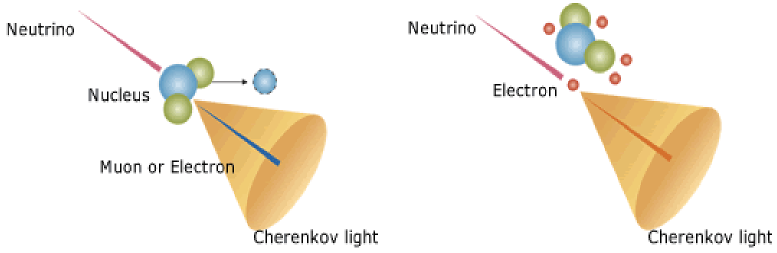
Super Kamiokande – the Detector



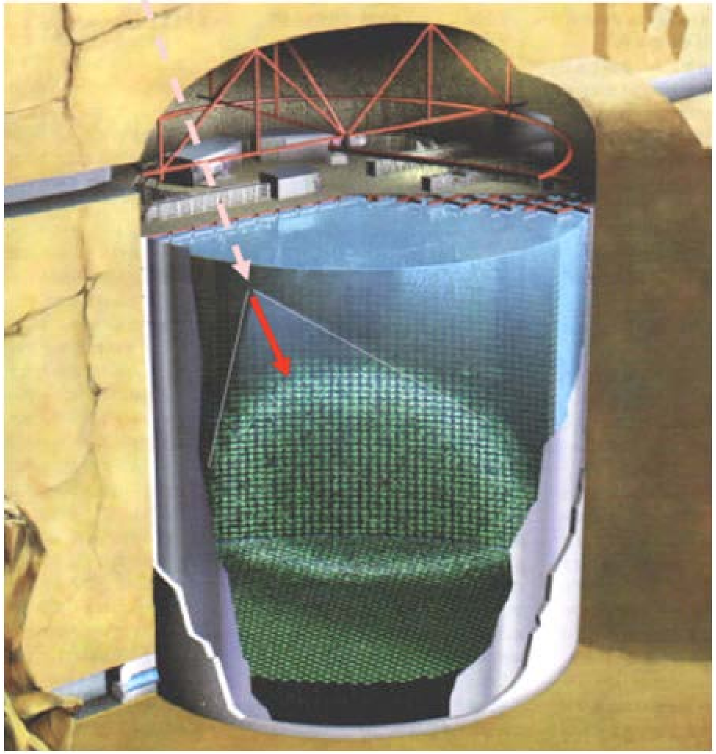
(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Super Kamiokande – Detection Concept

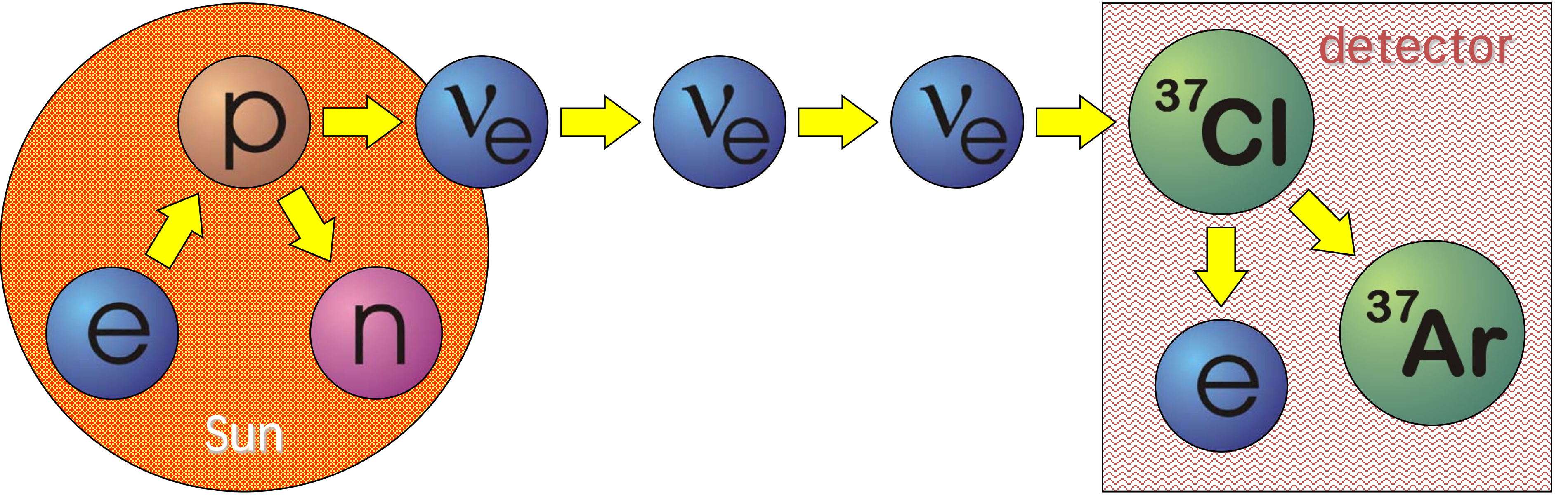
- Muon neutrinos interact with nucleons via charged current to produce ultra relativistic muons
- The muons travel faster than the speed of light in the detector (still slower than c)
- This produces a cone of Cherenkov light (same principle as a sonic boom)
- Light is detected by photo sensors

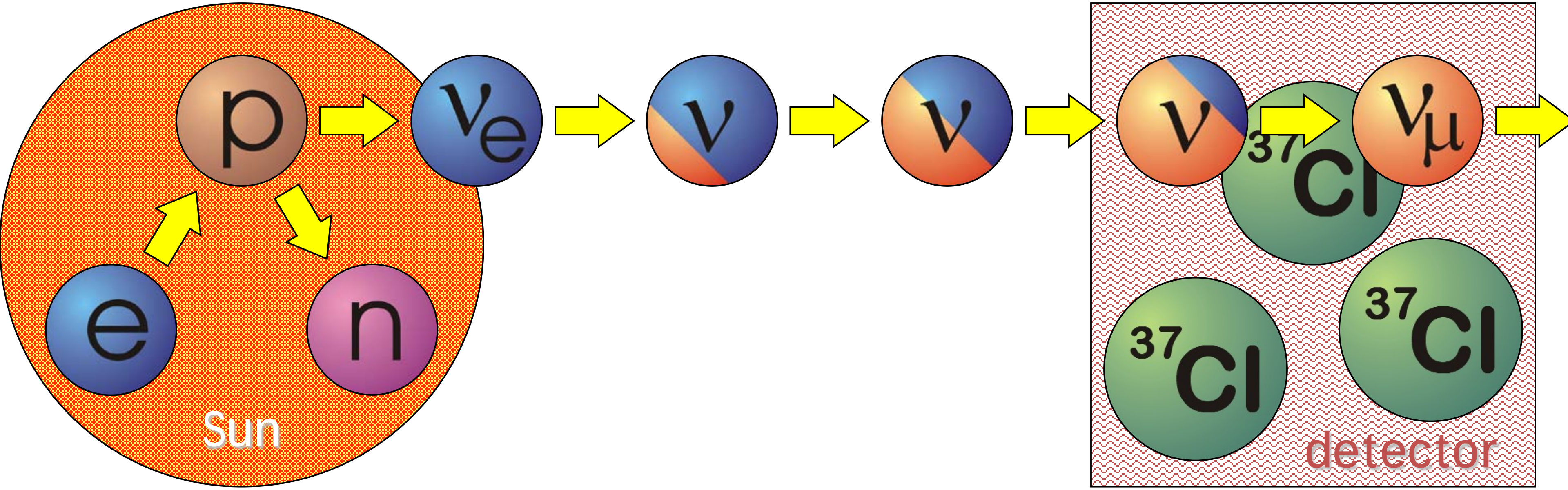


The generated charged particle emits the Cherenkov light.



Neutrino conversion is the solution of the problem





Neutrino oscillations

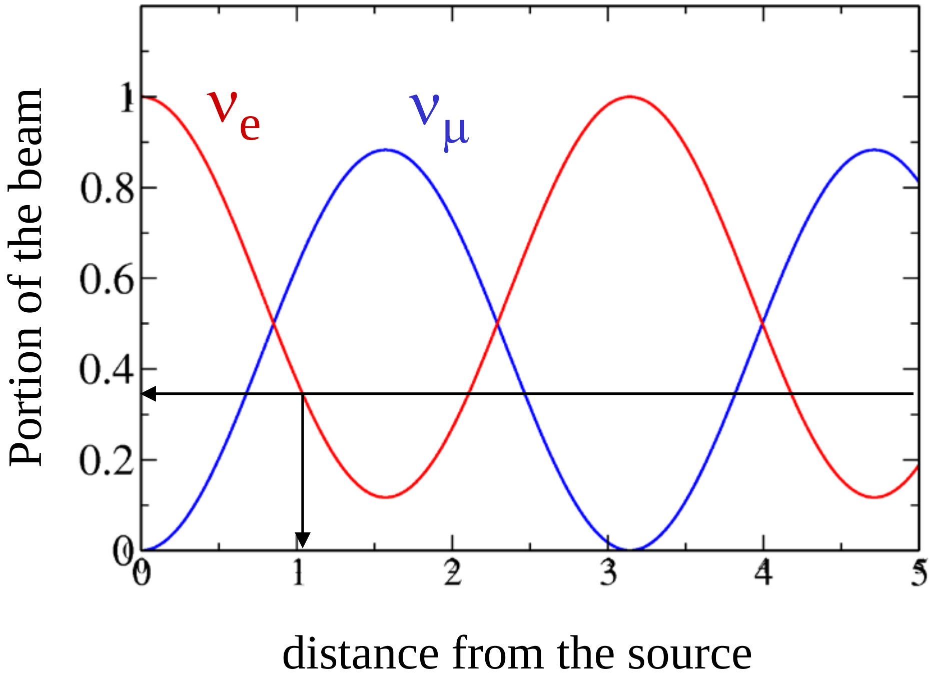
Electron e	Myon μ	Tau τ
e-Neutrino	μ-Neutrino	τ-Neutrino

Idea: when neutrinos have a mass, they may convert into each other!

Assumption: Mixture of

ν_e and ν_μ

Conversion of a neutrino beam with the distance from the neutrino source:

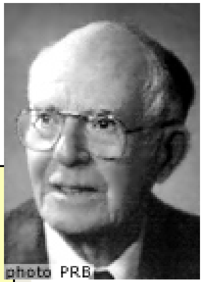


1998: Confirmation of the oscillations between Myon- and Tau-neutrinos with methods of Super-Kamiokande (Myon-neutrinos from the atmosphere)

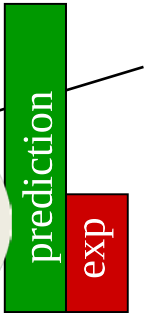
The solar neutrino problem

Sun
since 4.5 billion years
fusion

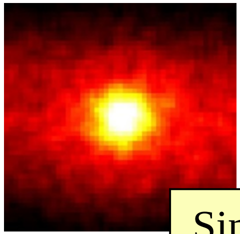
66 billion neutrinos/s/cm^2



since 1964: detection with
Homestake-experiment
expected: 1,5 reactions/d
measured: 0.5 reactions/d

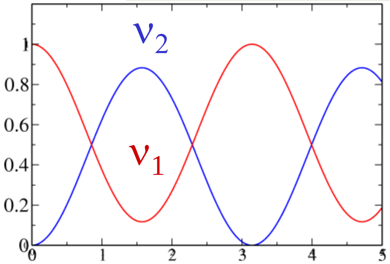


solar
neutrino
problem



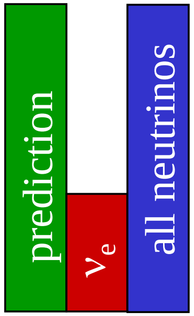
Since 1986 Kamiokande:
confirms Homestake

possible explanation:
neutrino-oscillation



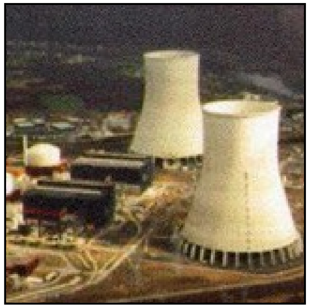
2002 SNO-experiment:
examines neutrino-oscillation

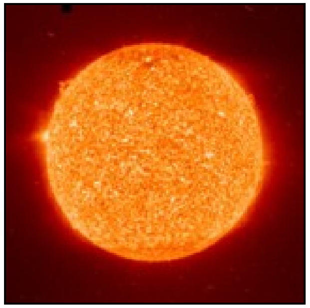
solar
neutrino
problem
solved!



Neutrinos as astrophysical messenger

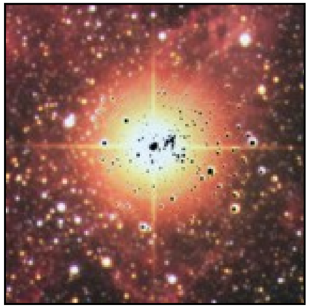
✓ nuclear reactors





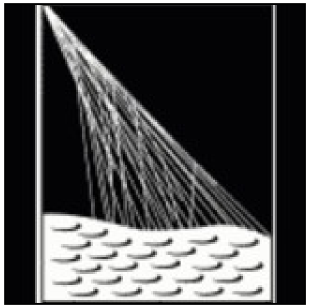
Sun ✓

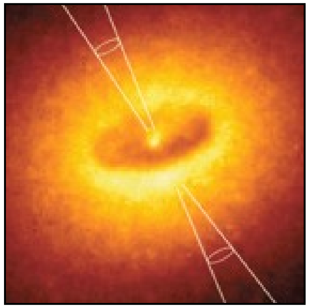
✓ particle accelerator



Supernovae
(collapsing stars)
SN 1987A ✓

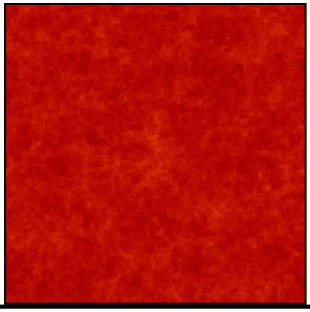
✓ earth atmosphere
(cosmic radiation)





astrophysical
accelerators soon ?

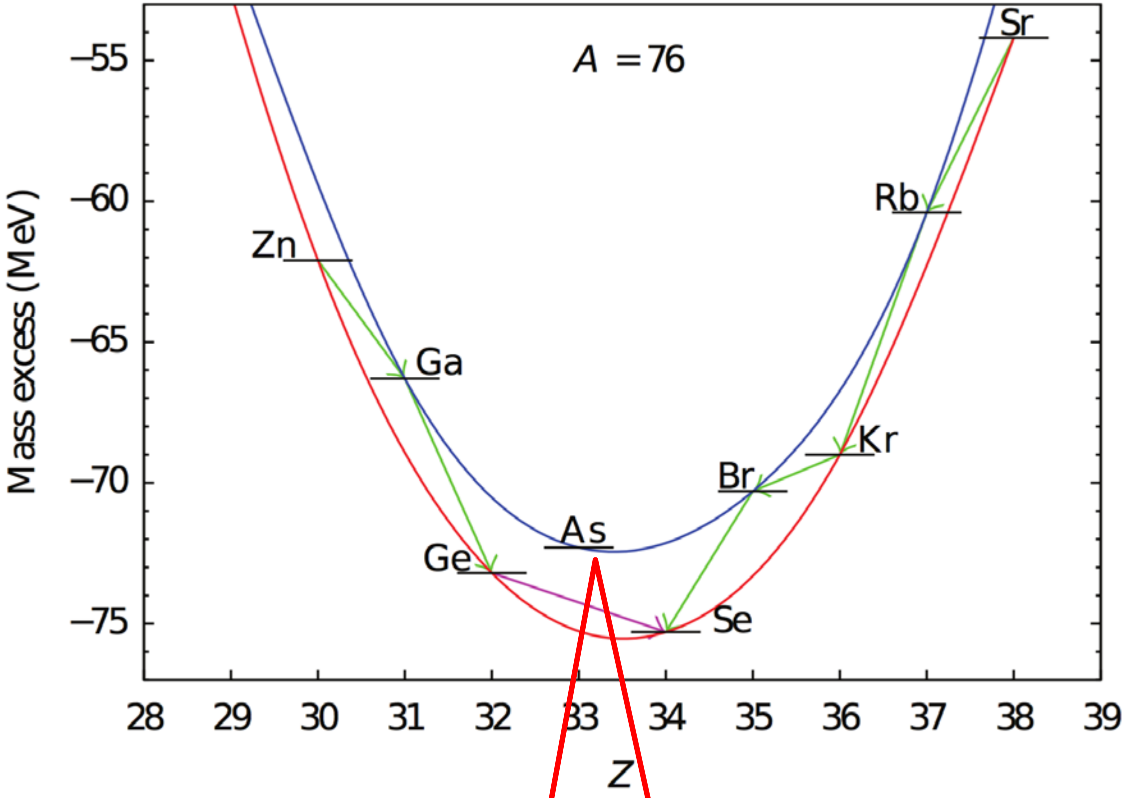
✓ earth crust
(natural radioactivity)



Big Bang of the Universe
(today 330 ν/cm^3)
indirect evidence

REMINDER

Two neutrino double beta decay

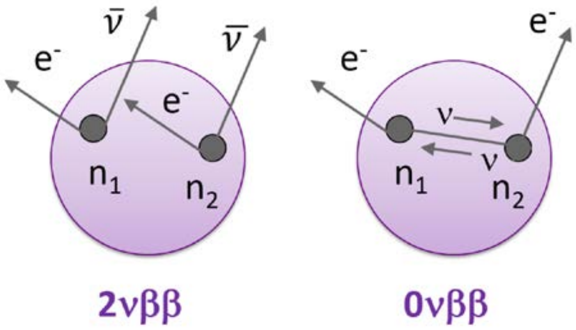


In some cases, the single beta decay is energetically forbidden.
Then the double beta decay becomes relevant

Isotope	$T_{1/2}$ (2ν) (y)
^{48}Ca	$(4.4 \pm 0.6)\cdot 10^{19}$
^{76}Ge	$(1.5 \pm 0.1)\cdot 10^{21}$
^{82}Se	$(0.92 \pm 0.07)\cdot 10^{20}$
^{96}Zr	$(2.3 \pm 0.2)\cdot 10^{19}$
^{100}Mo	$(7.1 \pm 0.4)\cdot 10^{18}$
^{116}Cd	$(2.8 \pm 0.2)\cdot 10^{19}$
^{128}Te	$(1.9 \pm 0.4)\cdot 10^{24}$
^{130}Te	$(1.5 \pm 0.1)\cdot 10^{20}$
^{150}Nd	$(8.2 \pm 0.9)\cdot 10^{18}$
^{238}U	$(2.0 \pm 0.6)\cdot 10^{21}$
^{136}Xe	$(2.1 \pm 0.2)\cdot 10^{22}$

Carl von Weizäcker

Dirac vs Majorana



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

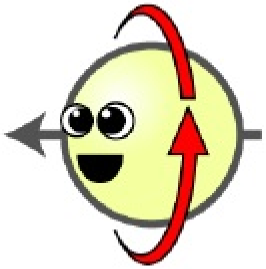
$$\nu_e + n \rightarrow p + e$$

Paul Dirac:
„The neutrino is **not identical** to the known antineutrino"

Ettore Majorana:
„The neutrino is **identical** to the known antineutrino"

Dirac vs Majorana

helicity:
projection of spin
onto momentum



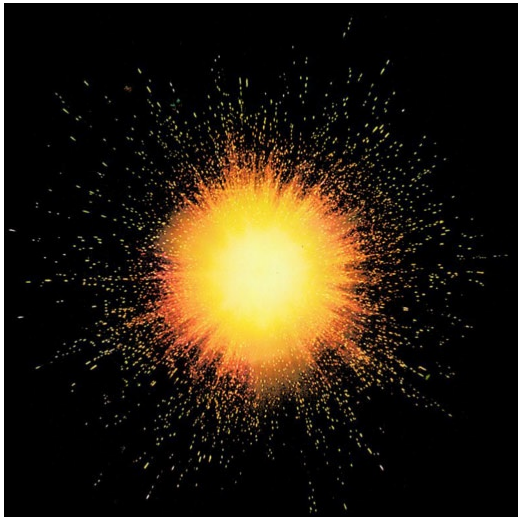
Experiments, so far, tell us:

- Neutrinos have left-handed helicity $\longrightarrow p \to n + e^{+} + \nu_e$
- Antineutrinos have right-handed helicity $\longrightarrow n \to p + e^{-} + \bar{\nu}_e$

Paul Dirac:
„Even if the neutrino flips its helicity it is still a fundamentally different particle. The reaction is not possible"

Ettore Majorana:
„Neutrino only has the wrong helicity, if it can flip the helicity this reaction should be possible"

Why do we care if the neutrino has Majorana nature?

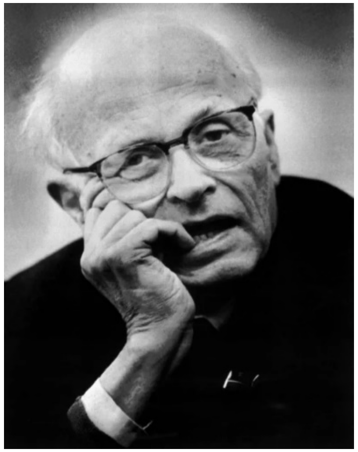


Matter asymmetry can be produced if

… Baryon number is violated

… Lepton number violation can be converted to
Baryon number violation

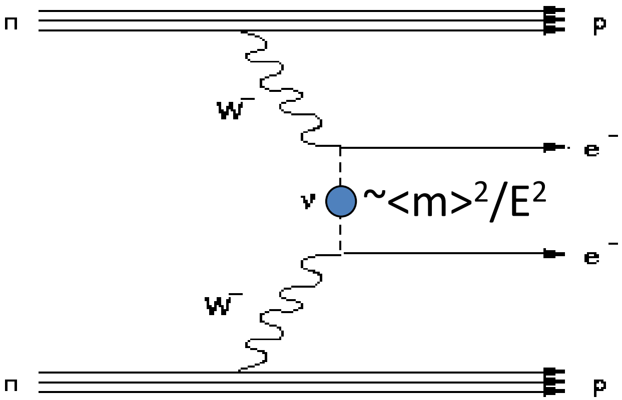
… hence we search for Lepton number violation
= Majorana nature of neutrinos



Andrei Sacharow, 1967

Neutrinoless ββ-decay

If neutrino are massive and Majorana particles, due to m^2 $\overline{\psi}_R^C \psi_L$ term in Lagrangian one can observe 2β0ν

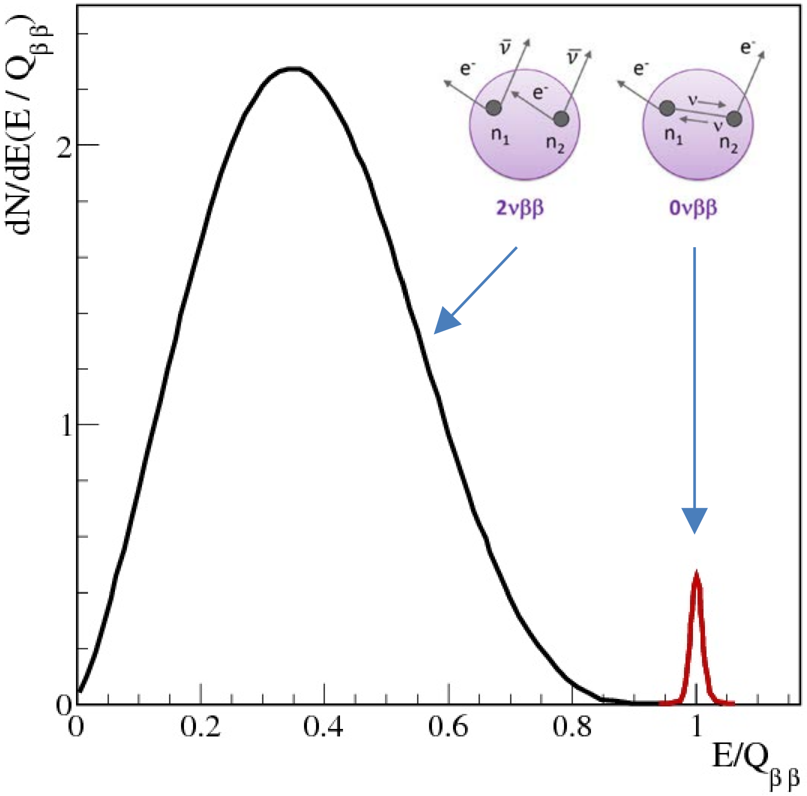


Golden plated channel:

a) 2 electrons
b) $E_{\beta 1}$+ $E_{\beta 2}$=$Q_{\beta\beta}$

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

The experimental signature

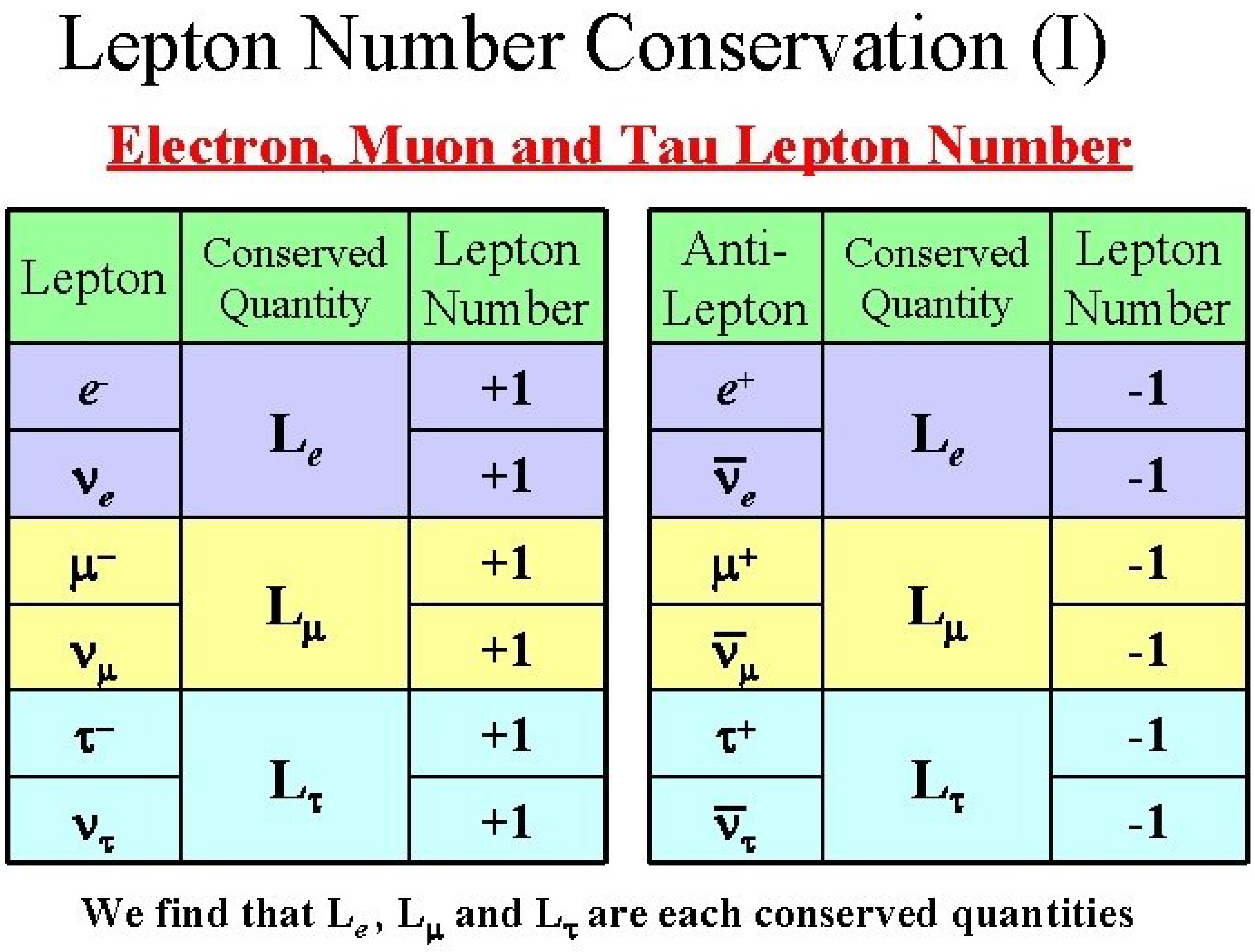


- 2νββ: neutrinos and electrons share the energy

- 0νββ: the electrons get all the energy

= energy of the two electrons
total energy released in the decay

Appendix: Lepton number



Lepton Number Conservation (I)

Electron, Muon and Tau Lepton Number

Lepton	Conserved Quantity	Lepton Number
e^-	L_e	+1
ν_e		+1
μ^-	L_μ	+1
ν_μ		+1
τ^-	L_τ	+1
ν_τ		+1

Anti-Lepton	Conserved Quantity	Lepton Number
e^+	L_e	-1
$\bar{\nu}_e$		-1
μ^+	L_μ	-1
$\bar{\nu}_\mu$		-1
τ^+	L_τ	-1
$\bar{\nu}_\tau$		-1

We find that L_e, L_μ and L_τ are each conserved quantities