Neutrino detectors

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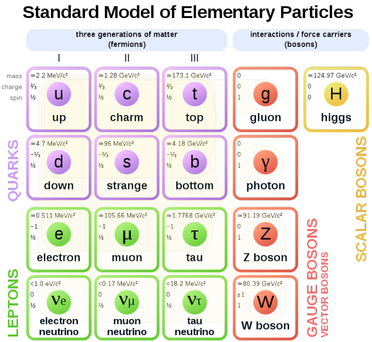
The weak interaction in the Standard Model

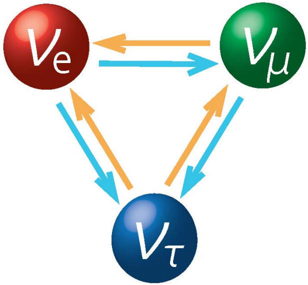
- "weak" $\rightarrow$ coupling constant
- mediator particles: $W^{\pm}, Z^0$
- neutrinos: only weak interaction
- β-decay



Neutrinos and their properties

"Tiny, Plentiful and Really Hard to Catch"
www.nytimes.com/2005/04/26/science/tiny-plentiful-and-really-hard-to-catch.html

- spin 1/2 fermions
- leptons
- three flavours (e, μ, τ)
- no charge
- non-zero mass
- parity violating (CP violating)
- very small cross sections
- neutrino flux on Earth $\sim 7 \cdot 10^{10} \frac{1}{\mathrm{cm}^2 \cdot \mathrm{s}}$

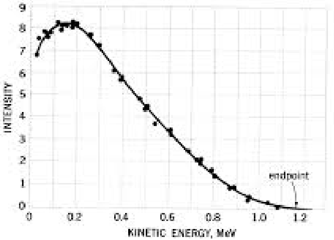


First prediction

"I've done a terrible thing, I have postulated a particle that cannot be detected." - Wolfgang Ernst Pauli /1930/

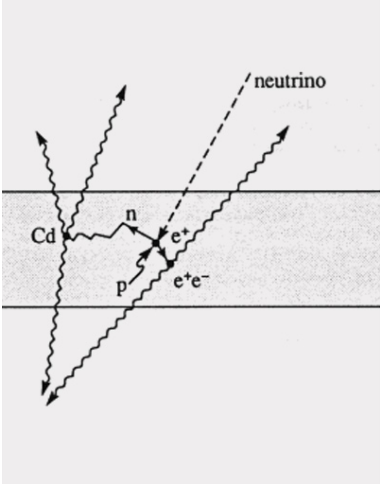
- contunous energy spectrum of β decay
- three body interaction, with neutral ν
- 0 ch., low x-section $\rightarrow$ can't be detected ?

FIGURE 11-1 **Energy spectrum of electrons emitted in the beta decay of Bi^{210}.** [From G. J. Neary, *Proc. Phys. Soc. (London)*, **A175:** 71 (1940).]



The Reines-Cowan experiment

- high flux (atomic reactor)
- inverse β decay: $p + \nu_e \rightarrow n + e^+$
- high volume of water (p)
- coincidence measurement of $e^+ + e^- \rightarrow \gamma\gamma$
- delayed signal of n capture: $^{108}Cd + n \rightarrow ^{109}Cd + \gamma$
- γ detected by photomultiplier tubes (PMT)
- Pauli sent them a case of Champage



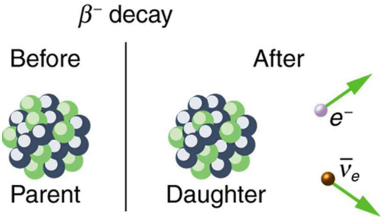
What kind of interactions can happen?

At first glance:

- negative β-decay: $n \to p + e^- + \bar{\nu}_e$
- positive β-decay: $p \to n + e^+ + \nu_e$
- inverse β decay: $p + \nu_e \to n + e^+$
- electron capture: $p + e^- \to n + \nu_e$
- elastic scattering: $e^- + \nu \to e^- + \nu$
- etc...

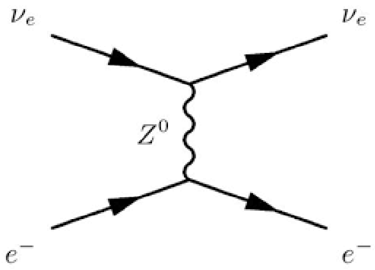
Fundamentally:

- neutral current
- charged current



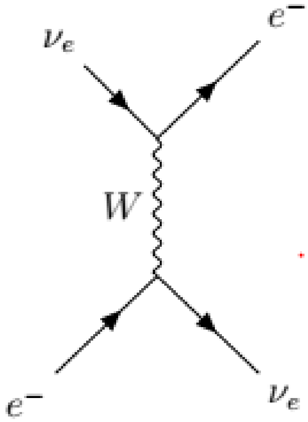
Neutral current interaction

- mediated by Z^0 boson
- no charge is interchanged



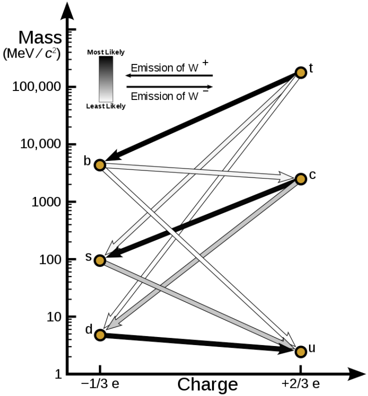
Charged current interaction

- mediated by $W^{\pm}$ boson
- charge is changed



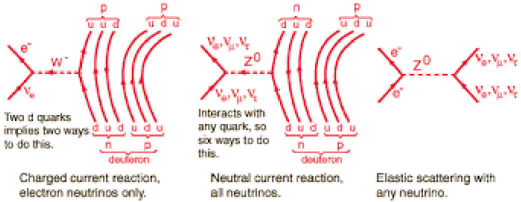
β-decay, decay scheme of quarks

- quark flavour is not conserved
- charged current process
- β-decay: $n \to p + e^- + \bar{\nu}_e$
- on quark level: $d \to u + e^- + \bar{\nu}_e$
- (flavour changing neutral current is not yet observed)



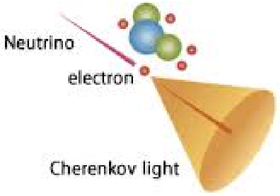
Neutrino detection

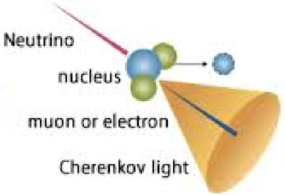
- cannot be detected directly
- CC interaction (flavour sensitive)
- NC interaction (flavour insensitive)
- (proton decay?)

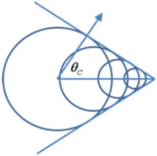


Cherenkov radiation

- charged particles are created/accelerated
- Cherenkov radiaton (scintillation,others...)
- transparent medium, with $n > 1$
- PMT-s detect the γ
- orientation can be determined
- ν_μ and ν_e may be distinguishable



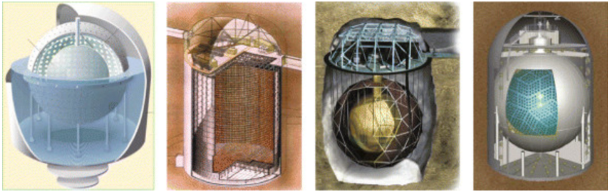


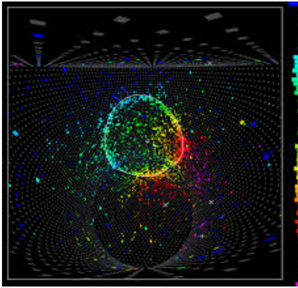


$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$$

Usual experimental setup

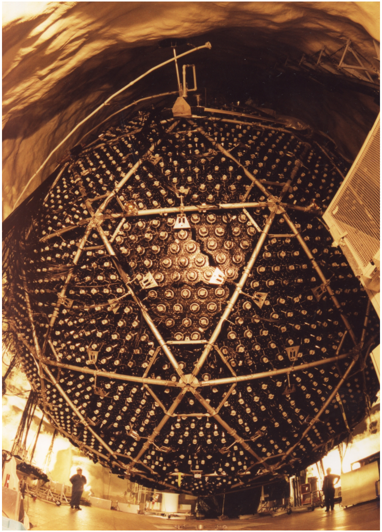
- high ν flux
- deep underground (shielding)
- high volume of transparent matter
- water or ice
- lots of low-noise PMTs
- very long data taking periods
- very few events





Sudbury Neutrino Observatory (SNO)

- Canada, Sudbury
- tank of heavy water (1000 t)
- solar neutrinos
- both CC and NC
- could measure the ν_e separately



Results of SNO

- solar neutrino problem (1/3 of expected)
- first observation of solar neutrino oscillation (2001)
- neutrino oscillation (non-zero ν mass)
- flavour & mass eigenstates are different

$$P_{a\to b} = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

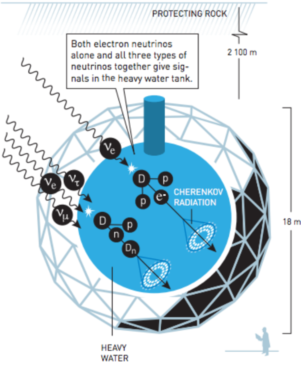
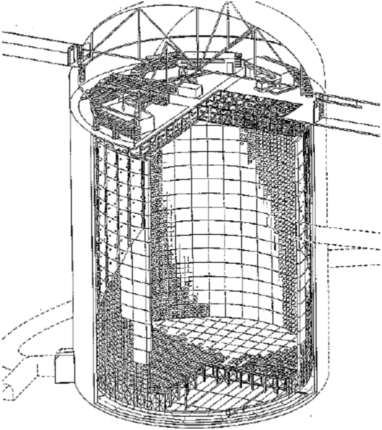


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

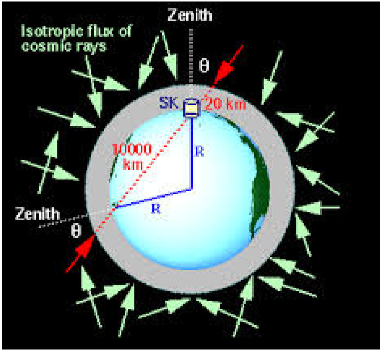
Super-Kamiokande (Super-K)

- Japan
- 50000 tons of water
- 13000 PMTs
- solar, atmospheric neutrinos
- proton decay, supernovae
- direction sensitive detection



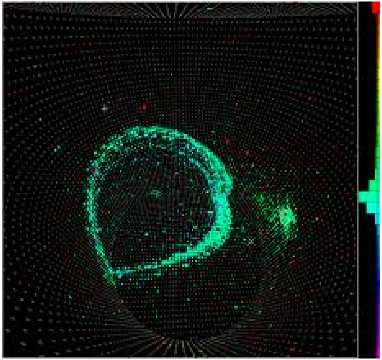
Results of Super-K

- neutrino oscillation of atmospheric neutrinos $\nu_\mu \leftrightarrow \nu_\tau$
- neutrino oscillation of solar neutrinos
- Δm^2 measurements



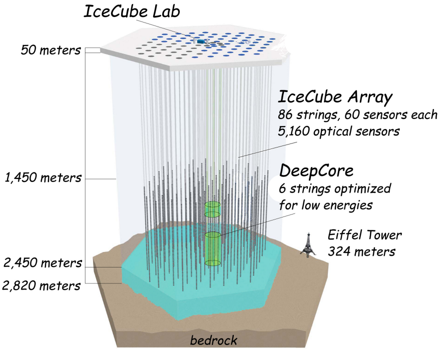
Results of Super-K

- first and only confirmed neutrino observation from a supernova (SN 1987A)
  $p + e^- \to n + \nu_e$
- Supernova Early Warning System (SNEWS)
  $\to$ no observations so far (since 2005)
- no proton decay observed so far
- proton lifetime: $\tau_p > 5.9 \cdot 10^{34}$ year



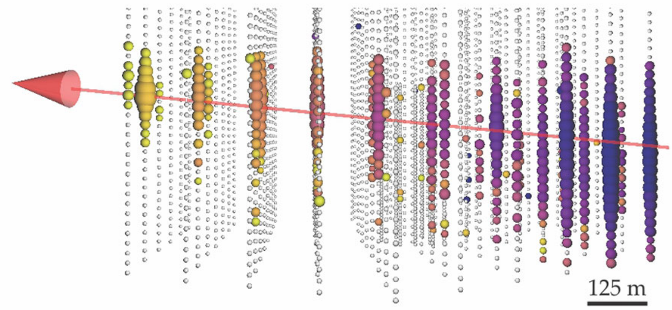
IceCube Neutrino Observatory

- Antartica
- $> 1\ \text{km}^3$ ice
- high energy neutrinos
- direction sensitive detection



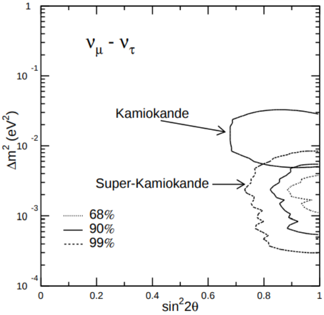
Results of IceCube

- netrinos from a blazar (TXS 0506+056)
- very high energy neutrinos (2000 TeV)
- Δm^2 measurements
- shadowing effect of the Moon



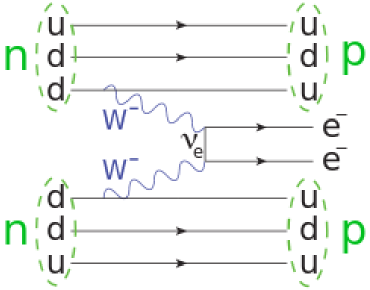
Future plans for neutrino detectors

- SNO→ SNO+
- KM3NET in the Mediterranian Sea
- Refinement of measurements
- Data collection
- Search for new physics



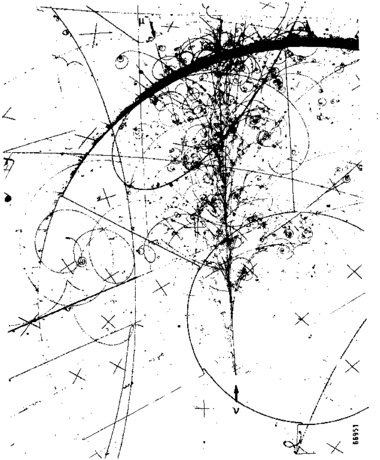
New physics with neutrinos

- proton decay
- sterile neutrino (only gravity)
- neutrinoless double β decay
- supernova detection
- sources of high energy cosmic neutrinos



Conclusions

- Mysterious particles since the beginning
- Lots of uncertainties up until today
- Neutrino-oscillation is not incorporated into the Standard Model
- Challenging for both experimentalists and theorists



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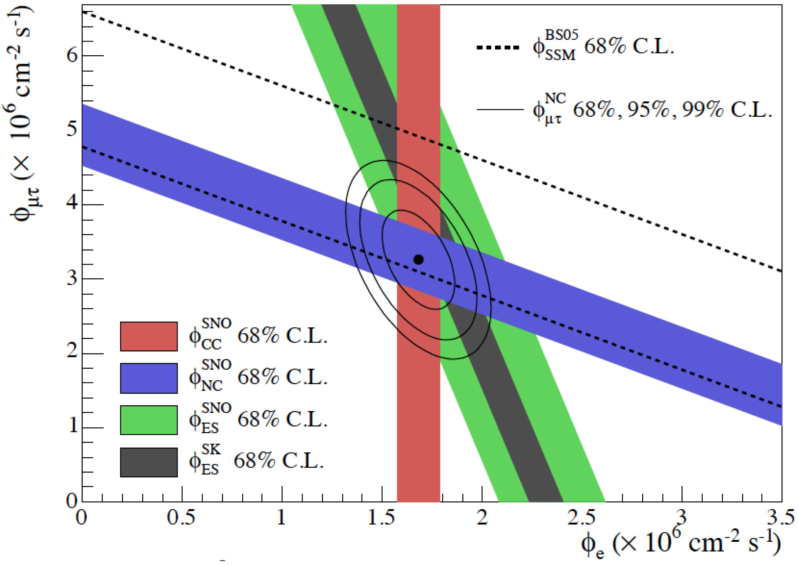
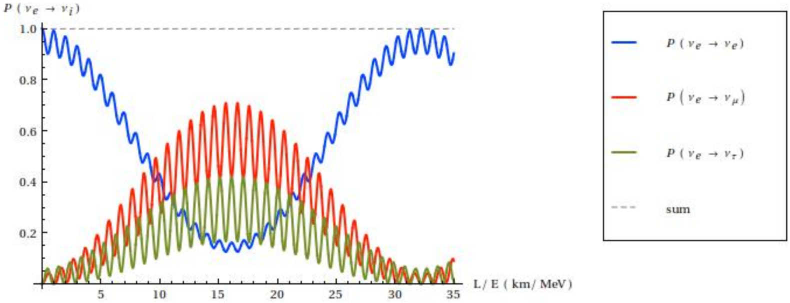
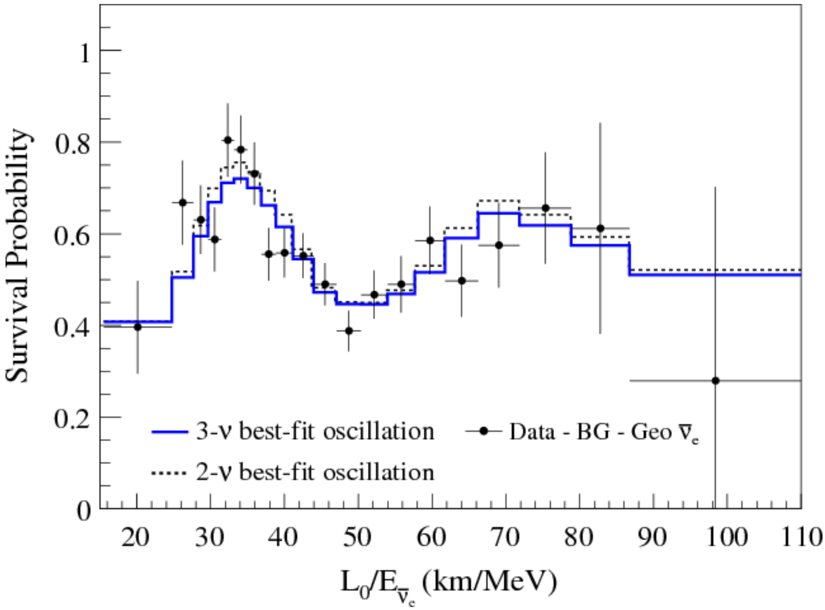
SNO solution for solar neutrino problem



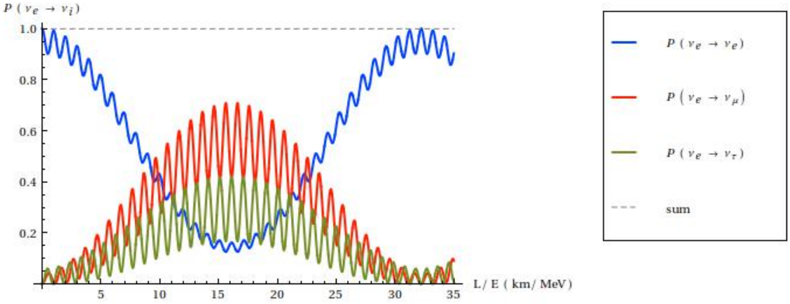
Example plot for neutrino oscillation



Experimental results for neutrino oscillation



Example plot for neutrino oscillation



Neutrino cross sections