Neutrino Physics: Lecture 1

Overview: discoveries, current status, future

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Plan of the course

Week 1	01 Feb	Introduction to neutrinos	02 Feb	Neutrinos before oscillations	
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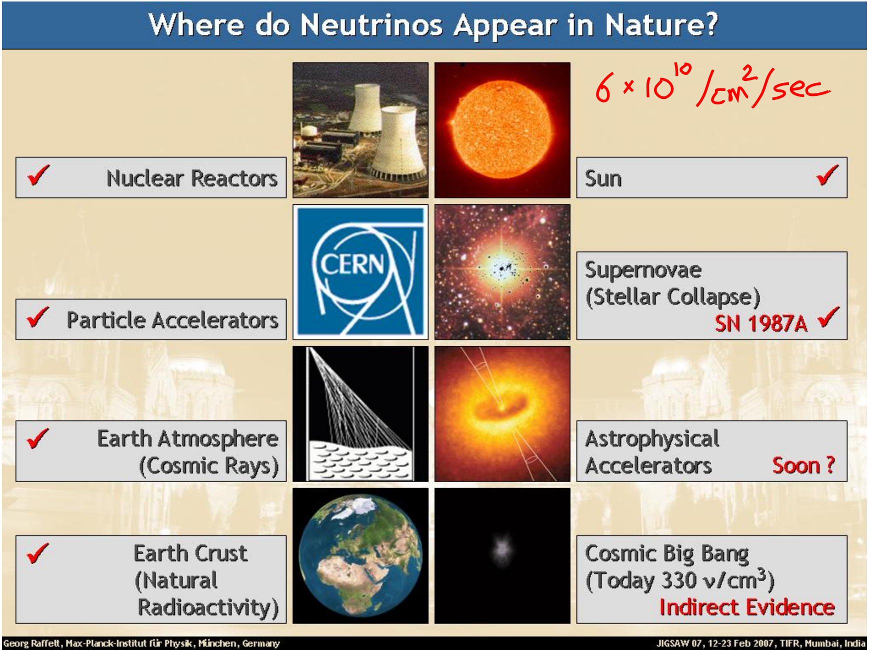
Omnipresent neutrinos



Unique features of neutrinos

The second most abundant particles in the universe

- Cosmic microwave background photons: 400 / cm^3
- Cosmic microwave background neutrinos: 330 / cm^3

The lightest massive particles

- A million times lighter than the electron
- No direct mass measurement yet

The most weakly interacting particles

- Invisible: do not interact with light
- Stopping radiation with lead shielding:
  - Stopping α, β, γ radiation: 50 cm
  - Stopping neutrinos from the Sun: several light years !

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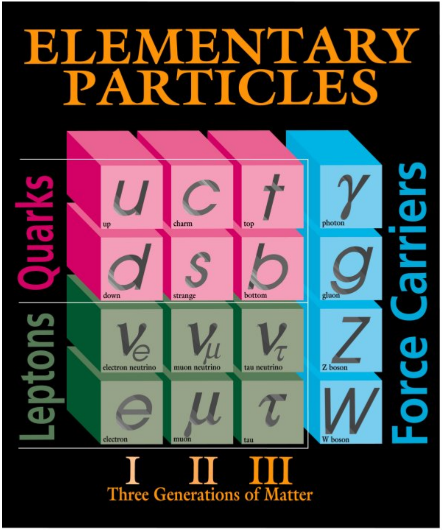
The Standard Model of Particle Physics



Fermilab 95-759

- 3 neutrinos: ν_e, ν_μ, ν_τ
- chargeless
- spin 1/2
- almost massless
- Only weak interactions

Outline

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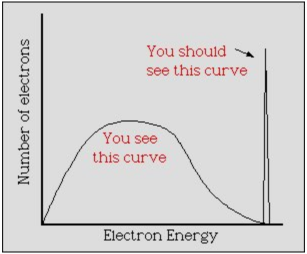
1. A brief history of neutrinos
2. Our current knowledge about neutrinos
3. The future of neutrino physics

The neutrino postulate: 1932

- Nuclear beta decay: $X \to Y + e^-$
- Conservation of energy and momentum $\Rightarrow$

  Electron energy $\approx m_X c^2 - m_Y c^2$
- But:



- Energy-momentum conservation in grave danger !!

A reluctant solution (Pauli): postulate a new particle

Does this new particle really exist ?

"But don't you see, Gershon - if the particle is too weakly interacting to detect, we can't just take it on faith that you've discovered it."

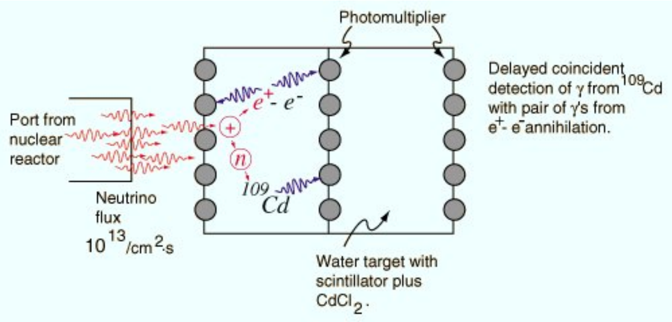
http://www.sciencecartoonsplus.com/pages/gallery.php

Discovery of electron neutrino: 1956

The million-dollar particle

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

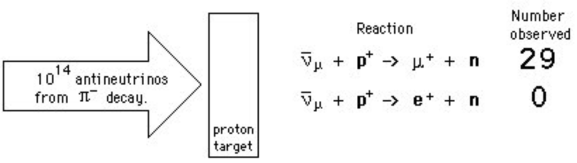
Reines-Cowan: Nobel prize 1995



Discoveries of ν_μ and ν_τ

Muon neutrino: an unexpected discovery (1962)

- Neutrinos from pion decay: $\pi^- \to \mu^- + \bar{\nu}_{(\mu)}$
- $\bar{\nu}_{(\mu)} + N \to N' + \mu^+$
- Always a muon, never an electron/positron



Steinberger-Schwartz-Lederman: Nobel prize 1988

Tau neutrino: expected, but hard to identify (2000)

DONUT experiment at Fermilab: $\nu_\tau + N \to \tau + N'$

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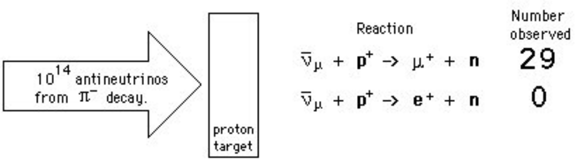

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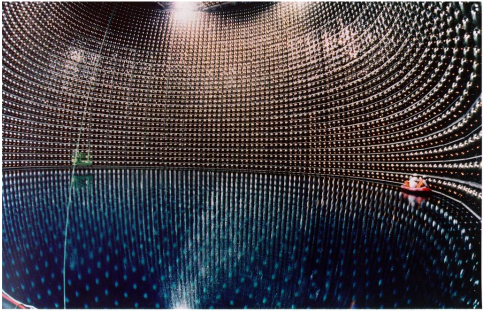
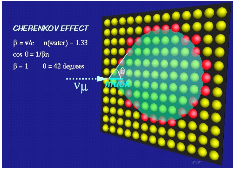
SuperKamiokande: 40 000 000 litres of water



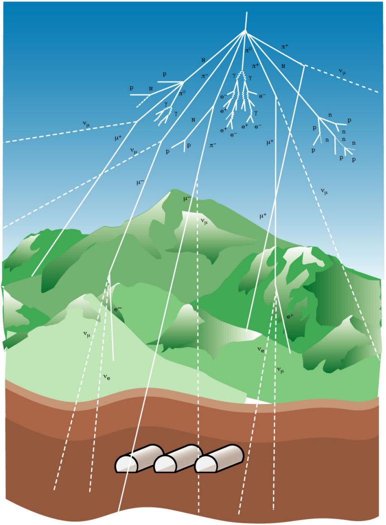


Cherenkov radiation

The largest current neutrino detector

- Neutrinos passing through SK: $\sim 6 \times 10^{11} / cm^2 / sec$
- Neutrino interactions in SK per day: ~ 10

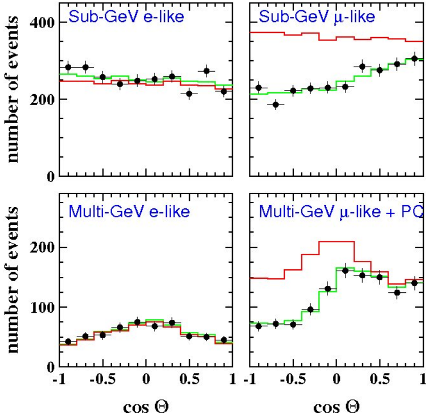
Neutrinos from cosmic rays (atmospheric neutrinos)

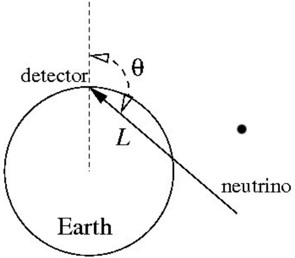


- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- "ν_μ" flux $= 2\times$ "ν_e" flux
- "Down" flux = "Up" flux

Atmospheric neutrino puzzle

Zenith angle dependence:





Super-Kamiokande

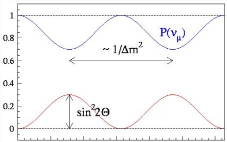
- Electron neutrinos match predictions
- Muon neutrinos lost while passing through the Earth !

Solution through "vacuum oscillations"

Prerequisites

- Neutrino flavours mix with each other ✓
- Neutrinos have different masses ✓
- ν_e do not participate in the oscillations ✓

Neutrino oscillations: ν_μ oscillate into ν_τ



$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

Mixing parameters

$\Delta m^2_{\rm atm} \approx (1.3\text{–}3.4) \times 10^{-3}$ eV^2

Mixing angle $\theta_{\rm atm} \approx 36°\text{–}54°$

Confirmed by "short baseline" experiments (K2K, MINOS)

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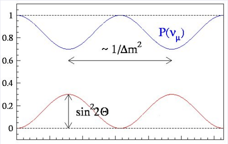

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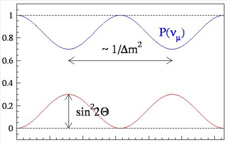

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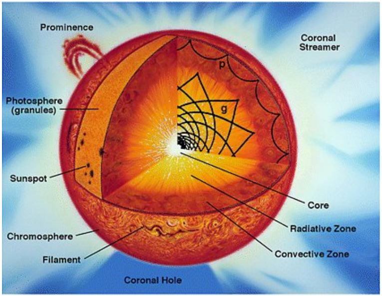
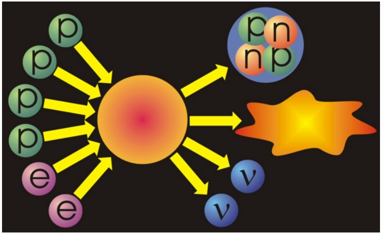
Neutrinos from the Sun (Solar neutrinos)





- Nuclear fusion reactions: mainly

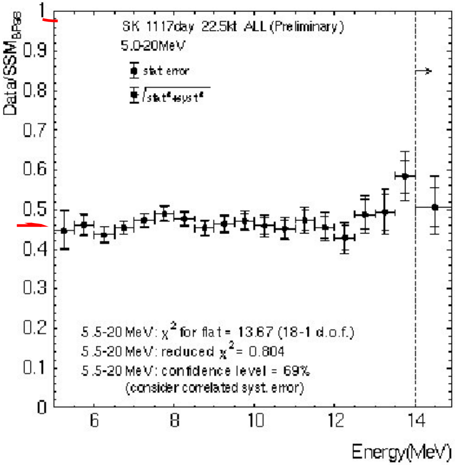
$$4\,{}^1_1\mathrm{H} + 2e^- \rightarrow {}^4_2\,\mathrm{He} + 2\nu_e + \mathrm{light}$$

- Neutrinos needed to conserve energy, momentum, angular momentum

Neutrinos essential for the Sun to shine !!

Davis-Koshiba Nobel prize 2002

Mystery of missing solar neutrinos



Super-Kamiokande

Where did the missing neutrinos (ν_e) go ?

Problem with our understanding of the Sun ?

Solar neutrino problem: unresolved for 40 years !

Solution of the solar neutrino puzzle

Prerequisites

- Neutrino flavours mix with each other
- Neutrinos have different masses
- Masses and mixing angles depend on matter density !

Survival probability of ν_e:

- $P(\nu_e \to \nu_e) \approx P_f \cos^2\theta_\odot + (1 - P_f)\sin^2\theta_\odot$
- P_f depends on: Δm^2, mixing angle $\theta_\odot$, density profile
- No oscillations ! (Mass eigenstates have decohered)

Mixing parameters

$$\Delta m^2_\odot \approx (7.2\text{–}9.5) \times 10^{-5}\ \text{eV}^2$$

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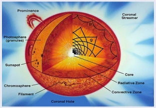
Outline

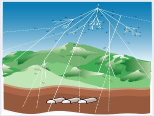
Summary of neutrino mixing parameters

Solar neutrino puzzle: 1960s – 2002



$\Delta m^2_\odot \approx 8 \times 10^{-5}$ eV^2, $\theta_\odot \approx 32°$

Atmospheric neutrino puzzle: 1980s – 1998



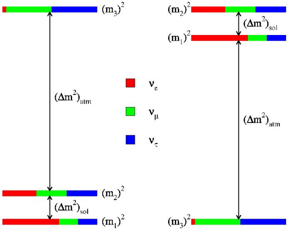
$\Delta m^2_{\rm atm} \approx 2 \times 10^{-3}$ eV^2, $\theta_{\rm atm} \approx 45°$

Reactor neutrino experiments

- No $\bar{\nu}_e$ are lost
- The "third" mixing angle "θ_{13}" is very small ($\theta_{13} < 12°$, may even be zero).

Neutrino masses and mixing: open questions

Mixing of ν_e, ν_μ, ν_τ $\Rightarrow$ ν_1, ν_2, ν_3 (mass eigenstates)



- Mass ordering: Normal or Inverted ?
- What are the absolute neutrino masses ?
- Are there more than 3 neutrinos ?
- Is there leptonic CP violation ?
- Is some new physics hidden in the data ?

Outline

Ongoing activities in neutrino physics

keV-energy neutrinos

- Neutrinoless double beta decay experiments:
  to determine if neutrinos are their own antiparticles

MeV-energy neutrinos

- Measuring the energy of the sun in neutrinos
- Geoneutrinos: neutrinos from the Earth's radioactivity
- Reactor neutrino experiments for θ_{13}

GeV-energy neutrinos

- Atmospheric neutrino measurements for mass ordering
- Long baseline experiments: production-detection distance
  $\sim$ 1000–10000 km

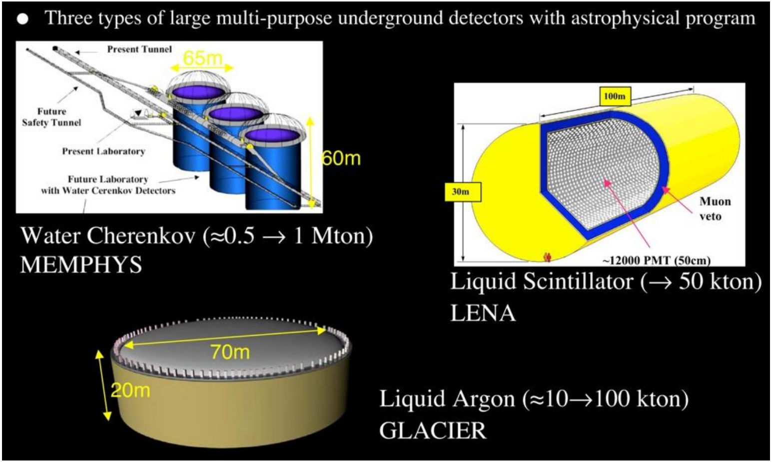
TeV-energy neutrinos

Astrophysical neutrinos: supernovae, GRBs, AGNs, etc.

Need bigger and better detectors !

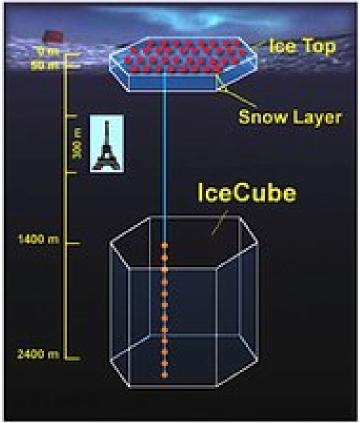
50 kiloton → 1 Megaton detectors

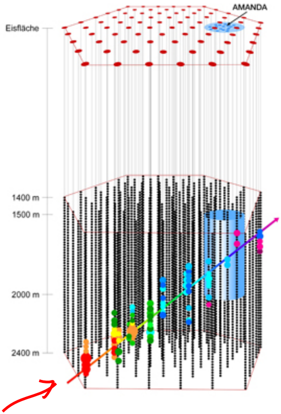
1 Megaton water = 1 000 000 000 litres



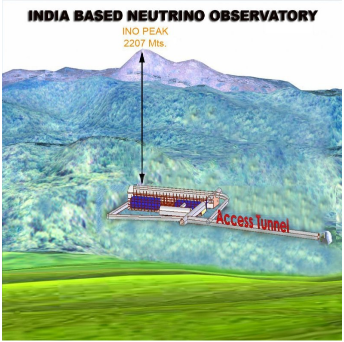
Below the antarctic ice: Gigaton IceCube

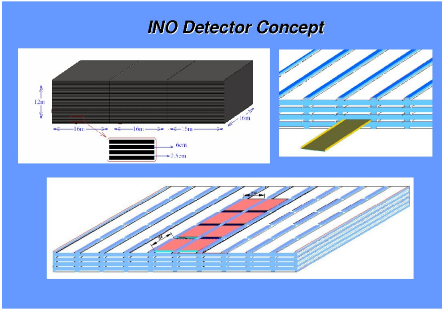
1 gigaton ice ≈ 1 000 000 000 000 litres





Coming soon inside a mountain near you: INO





India-based Neutrino Observatory

- Inside a tunnel, under a mountain
- 1 km rock coverage from all sides
- 50 kiloton of magnetized iron (50 000 000 kg)
- $\gtrsim$ 25 years: a lifelong project

Some open issues in neutrino physics

Neutrino masses and mixing

- Determination of masses and mixing parameters from data
- Are neutrinos their own antiparticles ?
- Signals of physics beyond the Standard Model
- Models for small ν masses and the bi-large mixing pattern

Astrophysics and cosmology

- Inverse supernova neutrino problem
- Effect of neutrino mixing on SN explosion mechanism
- Nucleosynthesis of heavy elements
- Creation of the matter-antimatter asymmetry

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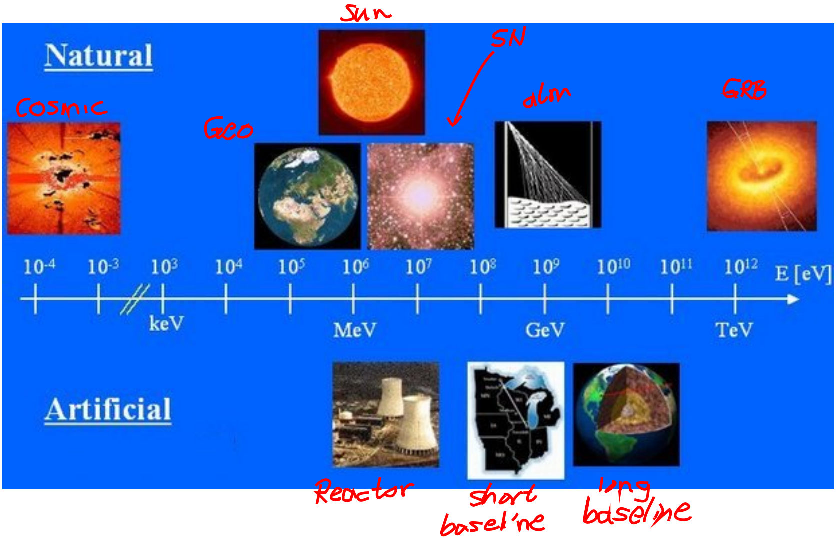
Elusive but omnipresent Neutrinos



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