The Invisibles

Stories from the wondrous world of neutrinos

Joachim Kopp, Fermilab

Outline

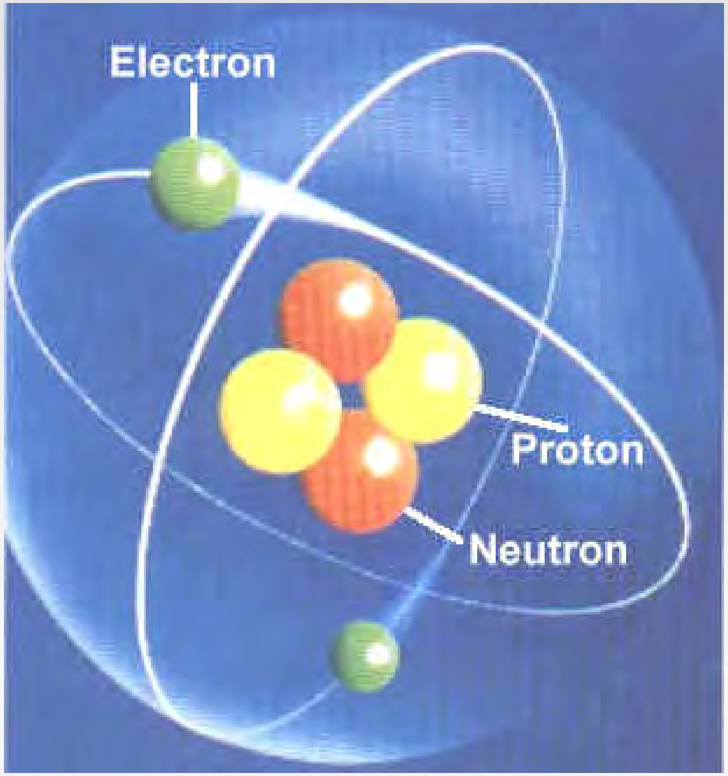
- What are neutrinos?
- The solar neutrino problem
- Neutrino oscillations
- Neutrino physics today
- Neutrinos faster than light?
- The future of neutrino physics

What are neutrinos?
— The beginnings —

The structure of matter

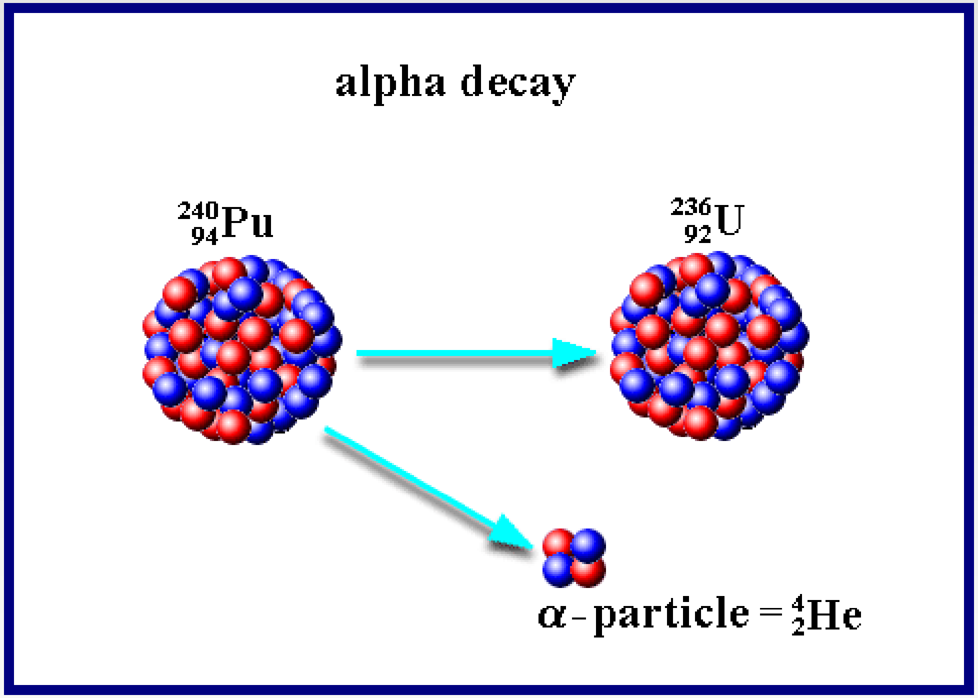
We know:

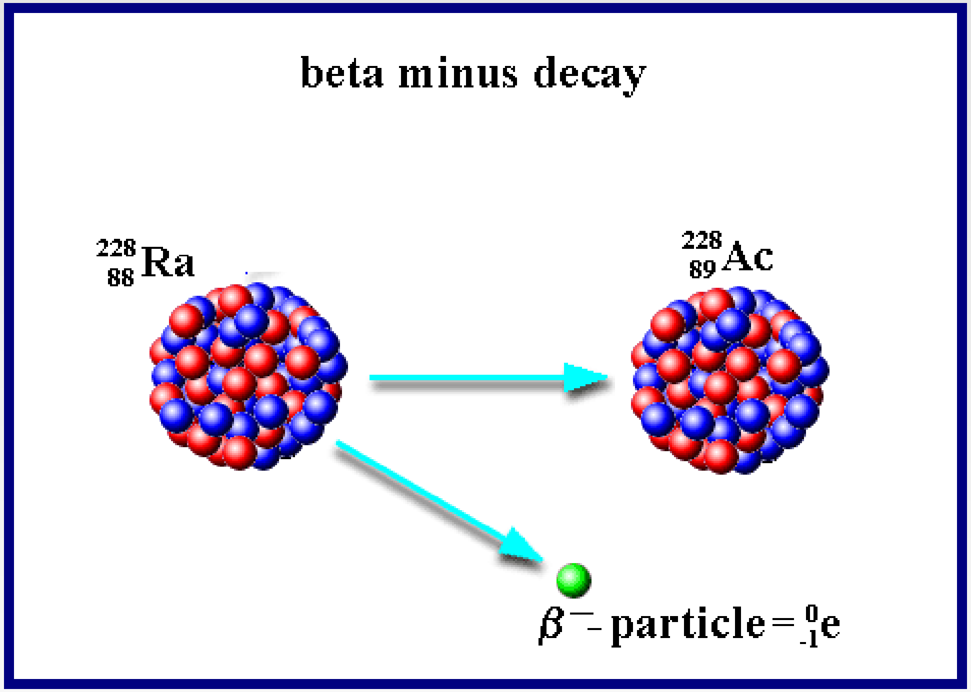
Matter consists of protons, neutrons, and electrons



Radioactive decays

Not all atomic nuclei are stable





Energy conservation in nuclear decay

In radioactive decay, part of the nuclear mass is converted into kinetic energy

$$E = m c^2$$

Observation (~ 1914 - 1930):

α-decay: The energy of the α-particle matches exactly the mass difference between the mother and daughter nuclei.

β-decay: The energy of the β-particle (electron) is *smaller* than the mass difference between the mother and daughter nuclei.

Energy conservation in nuclear decay

α-decay: $$E_\alpha = m_{Mother}c^2 - m_{Daughter}c^2$$

β-decay: $$E_\beta < m_{Mother}c^2 - m_{Daughter}c^2$$

Energy conservation in nuclear decay

α-decay: $$E_\alpha = m_{Mother}c^2 - m_{Daughter}c^2$$

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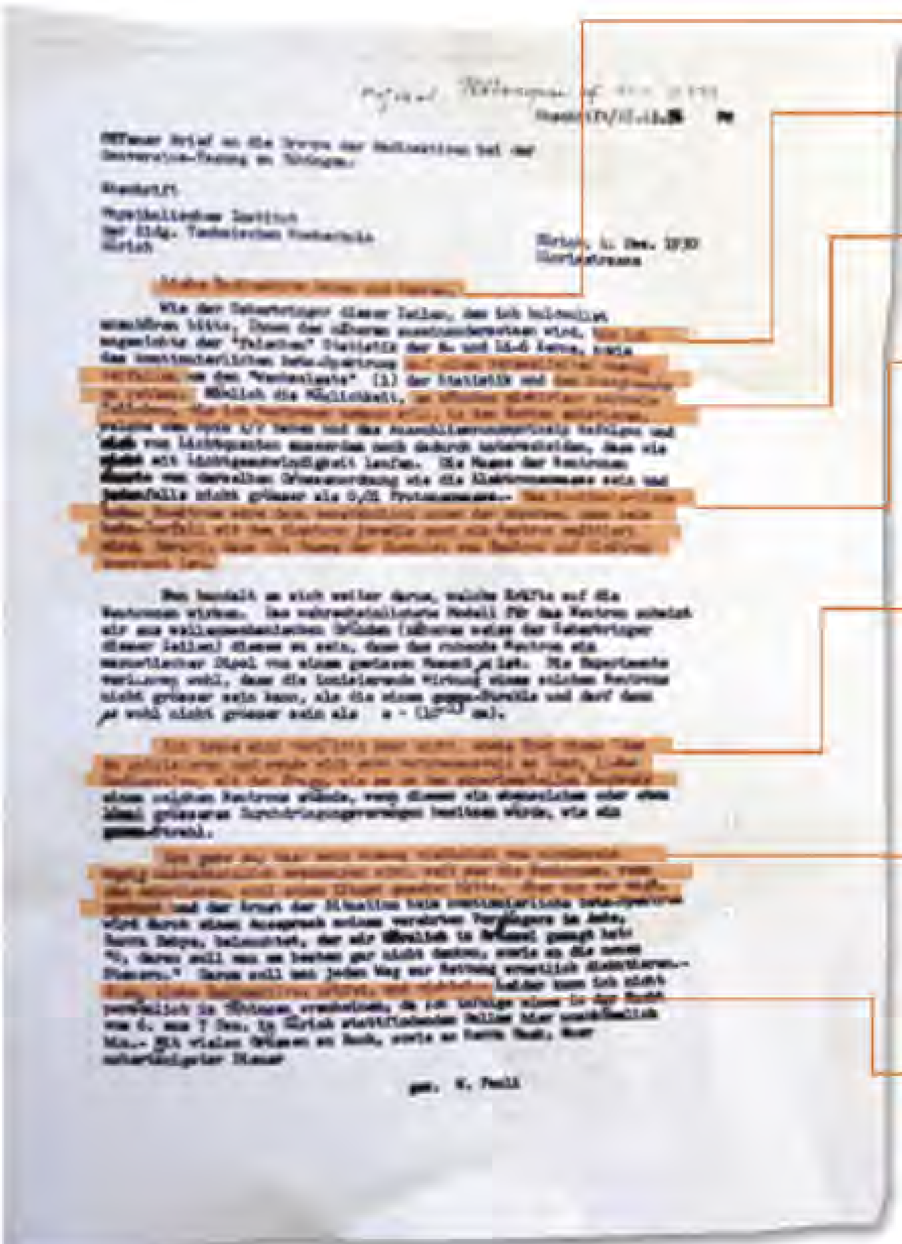
↑

Violation of energy conservation ???

Violation of energy conservation?

- Energy conservation is one of the most fundamental principles of physics
- Do we want to give up on this cornerstone of physics?
- Wolfgang Pauli, 1930: NO!

Pauli's letter from 1930



Dear Radioactive Ladies and Gentlemen

I have hit upon a desperate remedy to save … the law of conservation of energy

… there could exist electrically neutral particles, which I will call neutrons, in the nuclei …

The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive ones, with the question of how likely it is to find experimental evidence for such a neutron …

I admit that my remedy may seem quite improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing vetured, nothing gained …

Thus, dear radioactive ones, scrutinize and judge. Unfortunately, I cannot appear in Tübingen myself since my presence is required at a ball taking place … here in Zürich.

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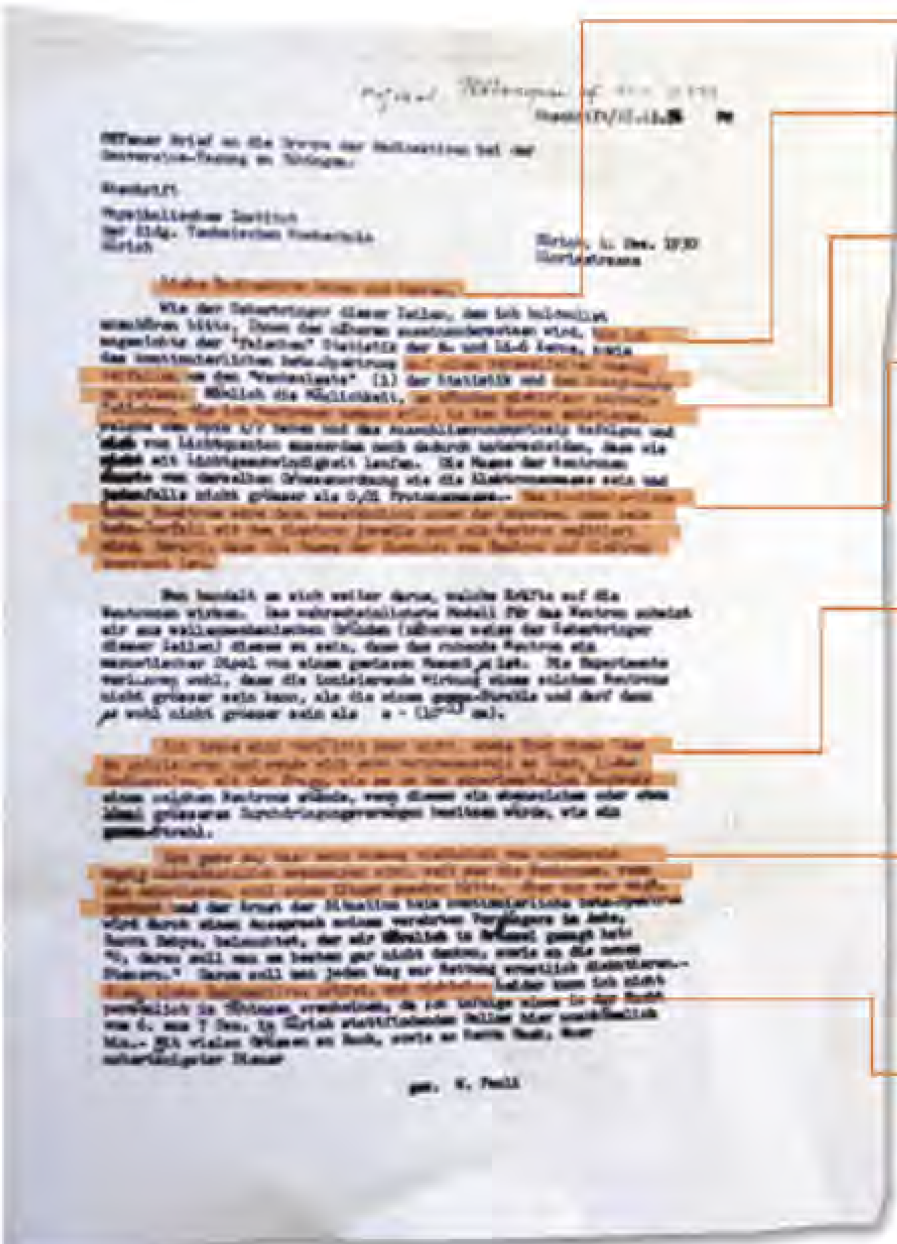

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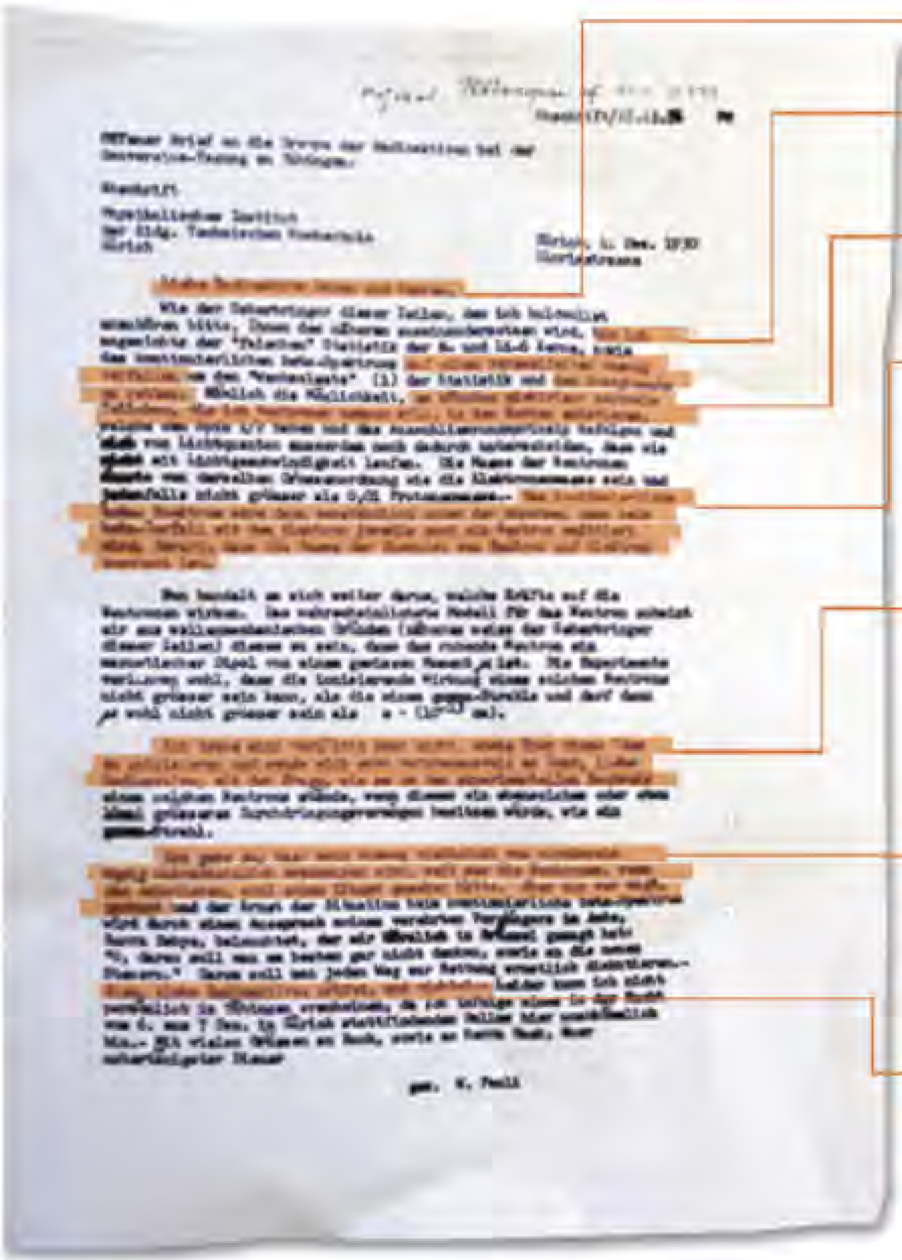

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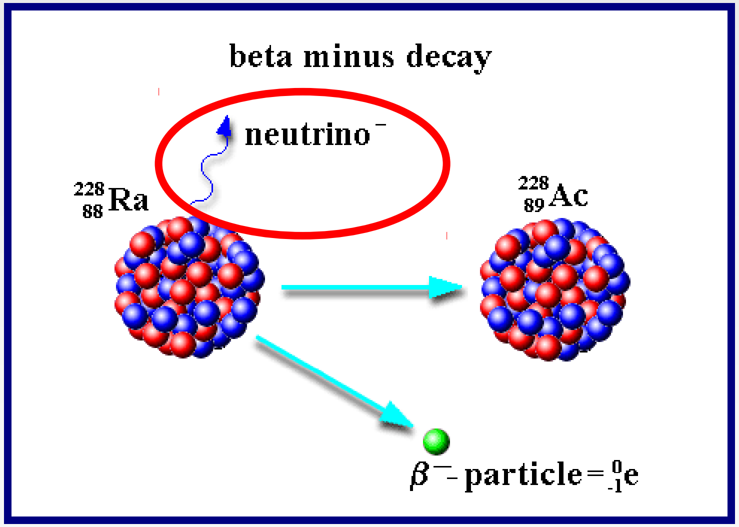
Pauli's idea

- The ”invisible” (and almost massless) neutrino (”ν”) carries away the missing energy in β-decay:

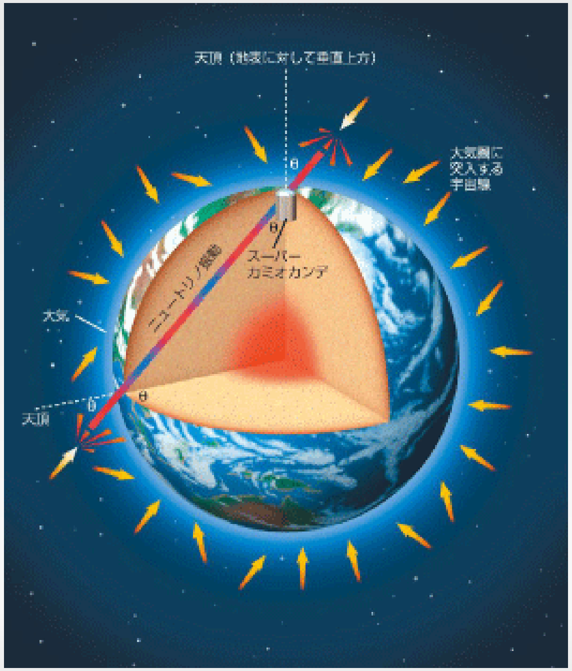
$$E_\beta + E_\nu = m_{Mother} c^2 - m_{Daughter} c^2$$



- And thus the neutrino was born ...

Detecting neutrinos

- Problem: How to detect an "invisible" particle?
- Solution: Neutrino interactions with normal matter are *very* weak (out of 100 billion neutrinos crossing the Earth, *one* gets absorbed!), but they have to exist — otherwise, neutrinos could not be produced in the decay of "normal" matter.



- Everything that can be produced, can also be absorbed

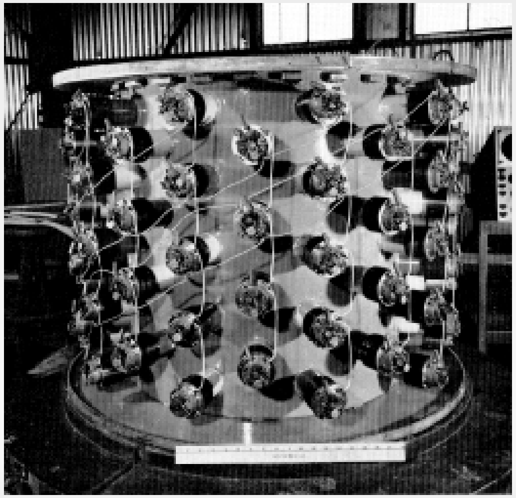
… another fundamental symmetry principle

The discovery of the neutrino

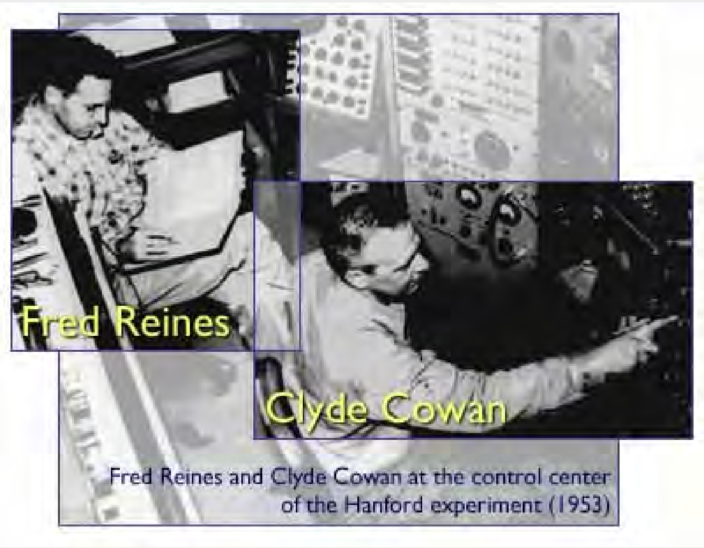
You need:

- Neutrinos. More neutrinos. Even more neutrinos.
  10 trillion neutrinos per second per cm^2.
- A particle detector – not too small either (say, few 100 kg)
- … and two physicists who are not afraid of a challenge.

Savannah River Reactor, SC



The first neutrino detector



C. Cowan & F. Reines

The discovery of the neutrino

20 July 1956, Volume 124, Number 3212 **SCIENCE**

Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire

A tentative identification of the free neutrino was made in an experiment performed at Hanford (*1*) in 1953. In that work the reaction

$$\nu_- + p^+ \rightarrow \beta^+ + n^0 \qquad (1)$$

was employed wherein the intense neutrino flux from fission-fragment decay in a large reactor was incident on a detector containing many target protons in

present work was done (*3*). This work confirms the results obtained at Hanford and so verifies the neutrino hypothesis suggested by Pauli (*4*) and incorporated in a quantitative theory of beta decay by Fermi (*5*).

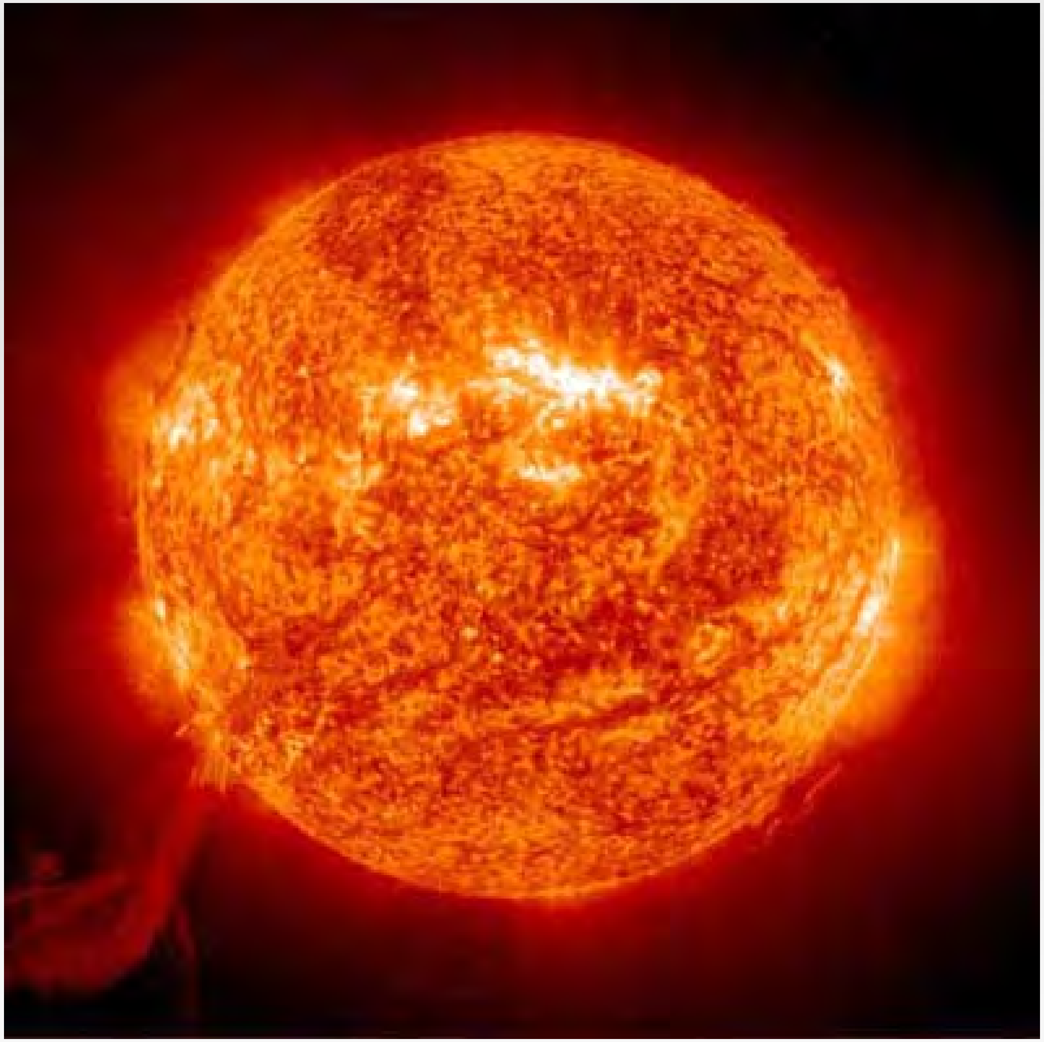
In this experiment, a detailed check of each term of Eq. 1 was made using a detector consisting of a multiple-layer (club-sandwich) arrangement of scintil-

both triads. The detector was completely enclosed by a paraffin and lead shield and was located in an underground room of the reactor building which provides excellent shielding from both the reactor neutrons and gamma rays and from cosmic rays.

The signals from a bank of preamplifiers connected to the scintillation tanks were transmitted via coaxial lines to an electronic analyzing system in a trailer van parked outside the reactor building. Two independent sets of equipment were used to analyze and record the operation of the two triad detectors. Linear amplifiers fed the signals to pulse-height selection gates and coincidence circuits. When the required pulse amplitudes and coincidences (prompt and delayed) were satisfied, the sweeps of two triple-beam oscilloscopes were triggered, and the pulses from the complete event were recorded photographically. The three beams of both oscilloscopes recorded signals from their respective scintillation tanks independently. The oscilloscopes were thus operated in parallel but with

The solar neutrino problem

Energy production in the Sun



Energy production through nuclear fusion:

$$4\,H \rightarrow He + 2\nu_e + 26.7\,MeV$$

⇒ no neutrinos ⇒ no nuclear fusion ⇒ no Sun ⇒ no life ⇒ no us

Detecting solar neutrinos

- Expected neutrino flux at the Earth:
  63 billion neutrinos per cm^2 per sec
- But: Extremely small interaction probability:
  ~ 1 neutrino interaction per day in a typical (~ 100 ton) detector
- ... and there's lots of cosmic radiation that can be misinterpreted as a neutrino signal.

Detecting solar neutrinos (2)

- Solution: Build detector underground to shield against cosmic radiation.
- Ray Davis (1960's): Homestake-Experiment

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Homestake gold mine (SD):
1.5 km underground
Active material: 615 t C_2Cl_4
A neutrino interaction converts a Cl atom to an Ar atom

$$\nu_e + {}^{37}_{17}Cl \rightarrow {}^{37}_{18}Ar + e^-$$

After several weeks, the 10 – 20 produced Ar atoms need to be extracted and counted.

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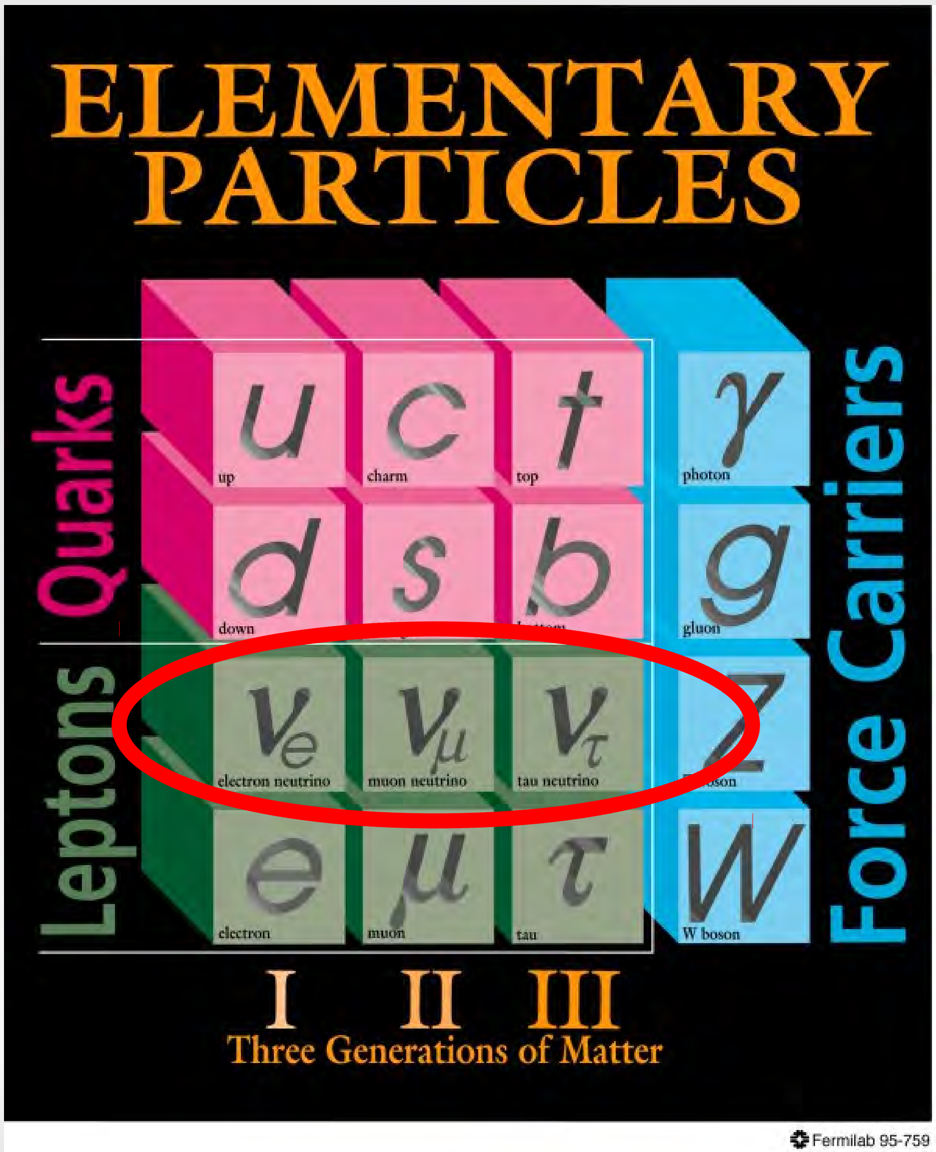
Result: 2/3 of the expected neutrinos are missing!

Where are the missing neutrinos?

- Wrong assumptions about the Sun?
  - All other data in very good agreement with solar models.
- Experimental error?
  - Davis' result confirmed by numerous other experiments.
- Neutrino decay?
  - decay into what?
- Neutrino oscillations!

Neutrino oscillations

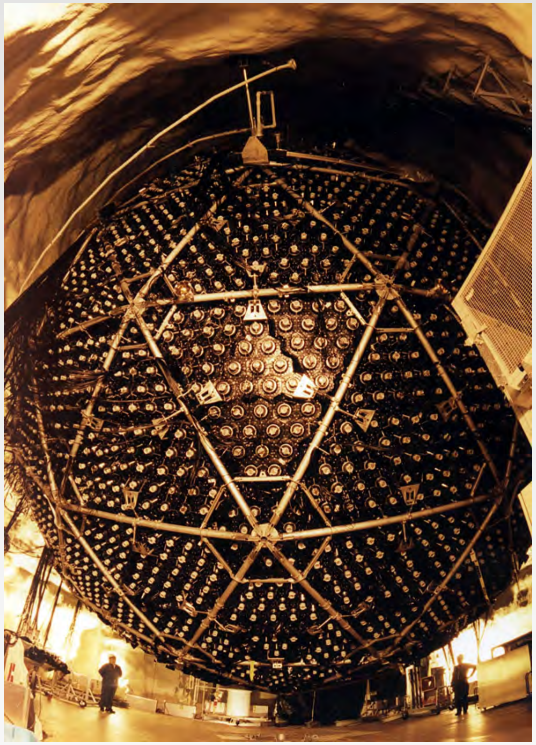
Neutrino oscillations



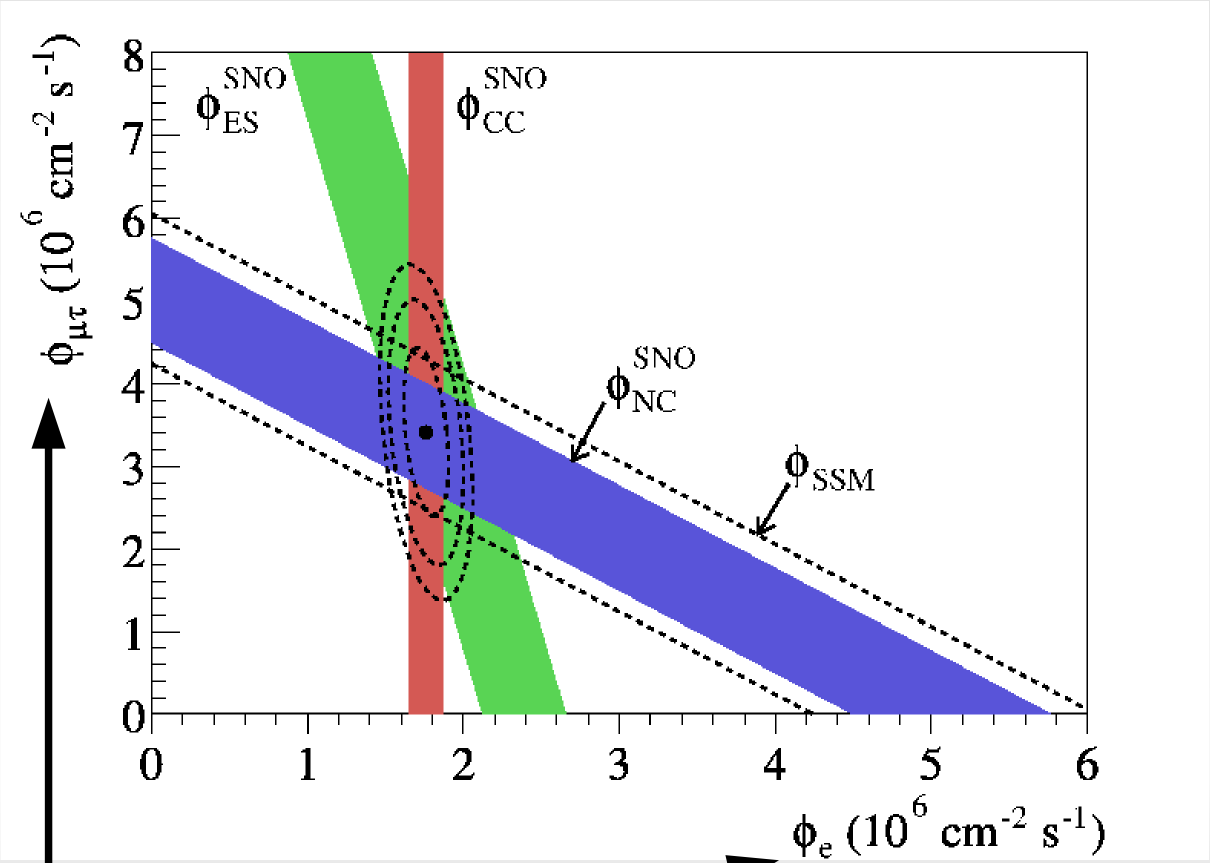
- There ae three neutrino ”flavors”
- The Sun produces only electron neutrinos
- muon and tau neutrinos ”invisible” to conventional solar neutrino detectors
- Conversion of ν_e into ν_μ or ν_τ?

Solving the solar neutrino problem

- 2002: Sudbury Neutrino Observatory, Canada
  Detection of solar ν_e *and* ν_μ, ν_τ: Total flux OK!



SNO
1 000 t D_2O

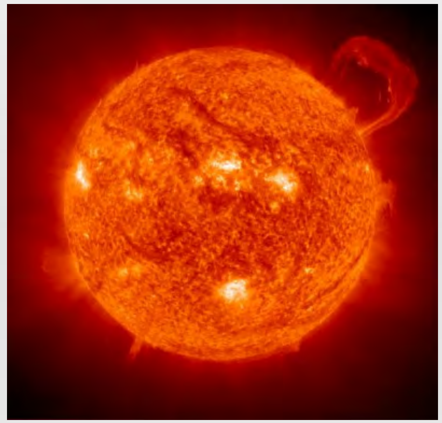


flux of ν_μ, ν_τ flux of ν_e

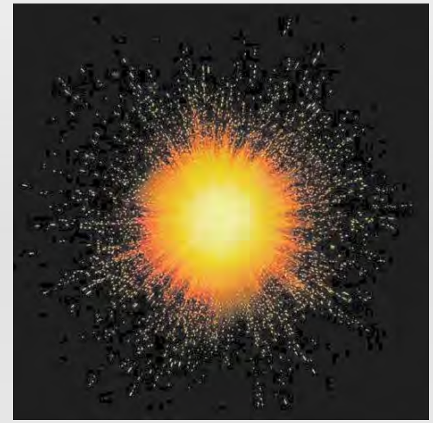
Neutrino physics today

A plethora of neutrino sources ...

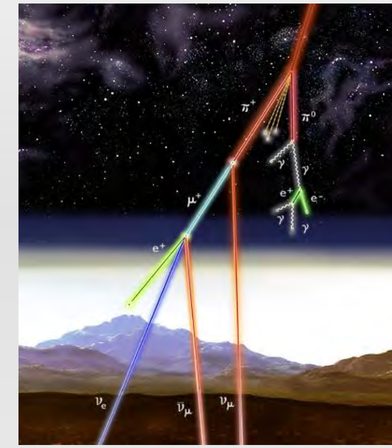
Nuclear reactors



The Sun

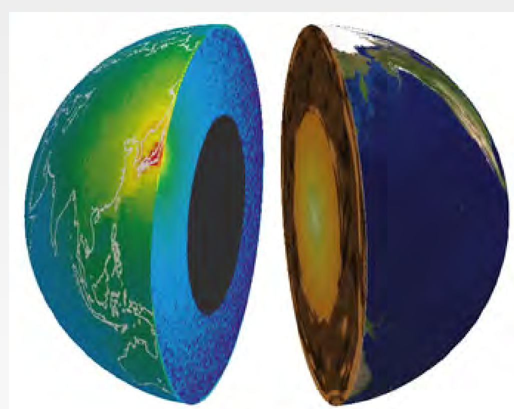


The Big Bang



Cosmic rays interacting with the atmosphere

Supernovae

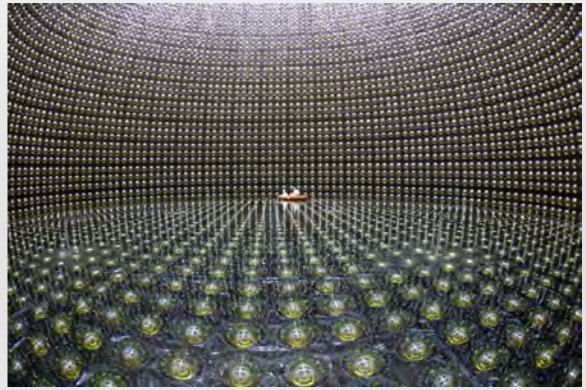


Radioactive decays inside the Earth

Particle accelerators

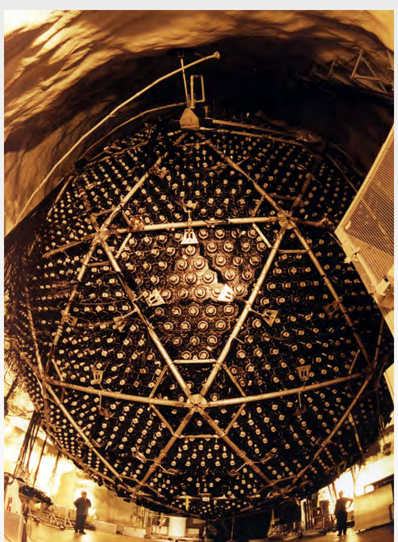
… and of detector technologies

Homestake:
615 t C_2Cl_4



Super-Kamiokande:
50 000 t ultra-pure H_2O

MINOS
5 400 t steel + plastic



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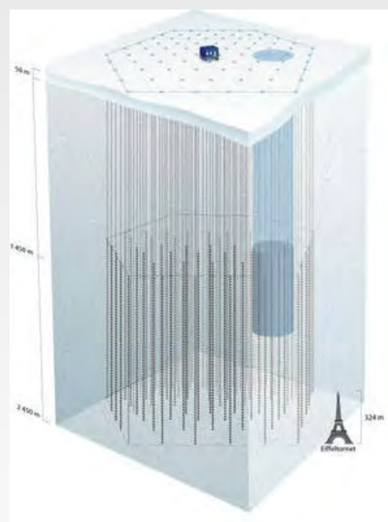
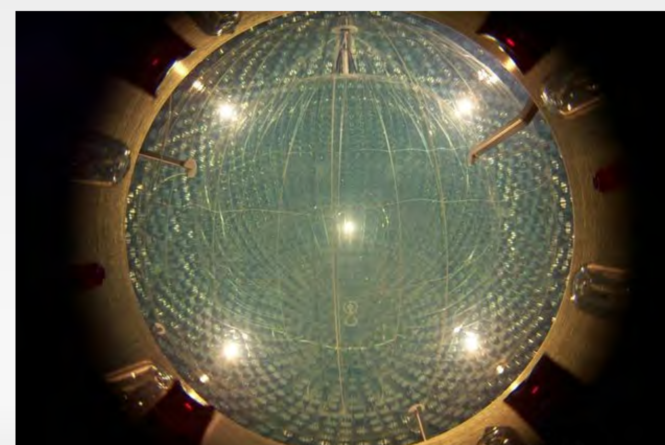


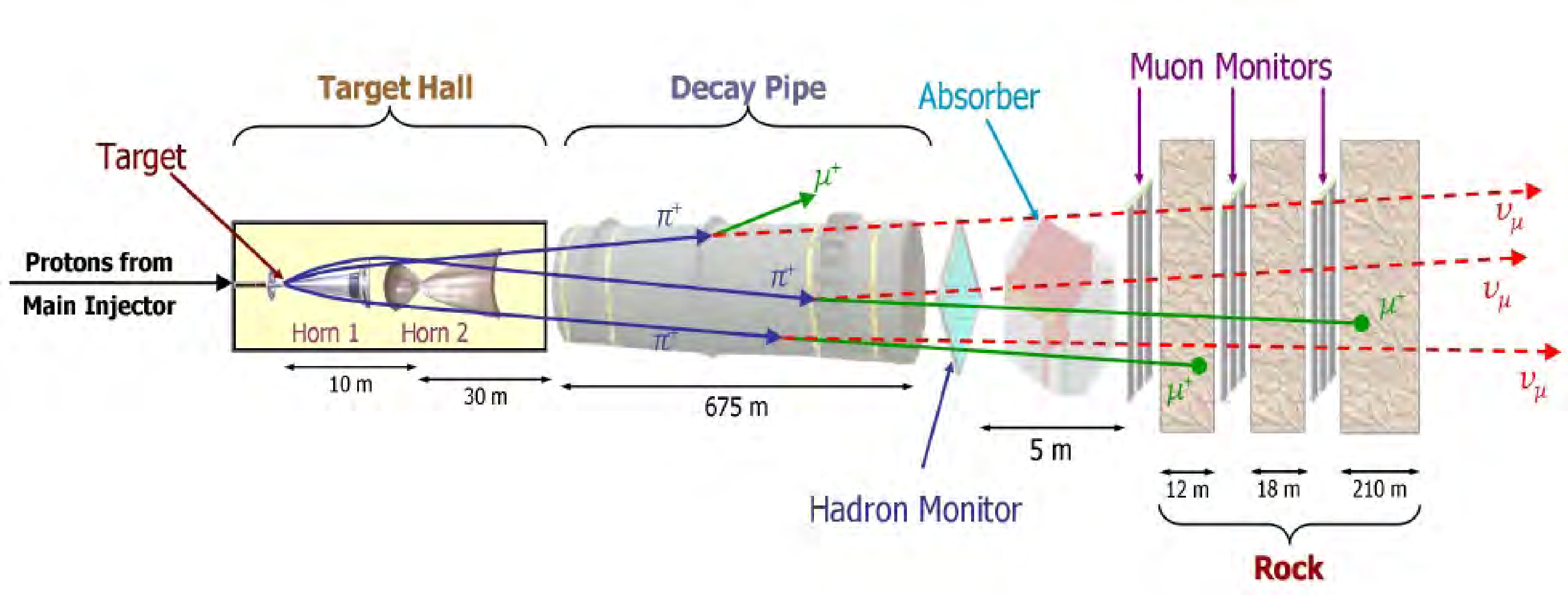
IceCube
1 $km^3 = 10^9$ t
of antarctic ice



Borexino
1 300 t liquid scintillator

MINOS @ Fermilab

- ”Main Injector Neutrino Oscillation Search”

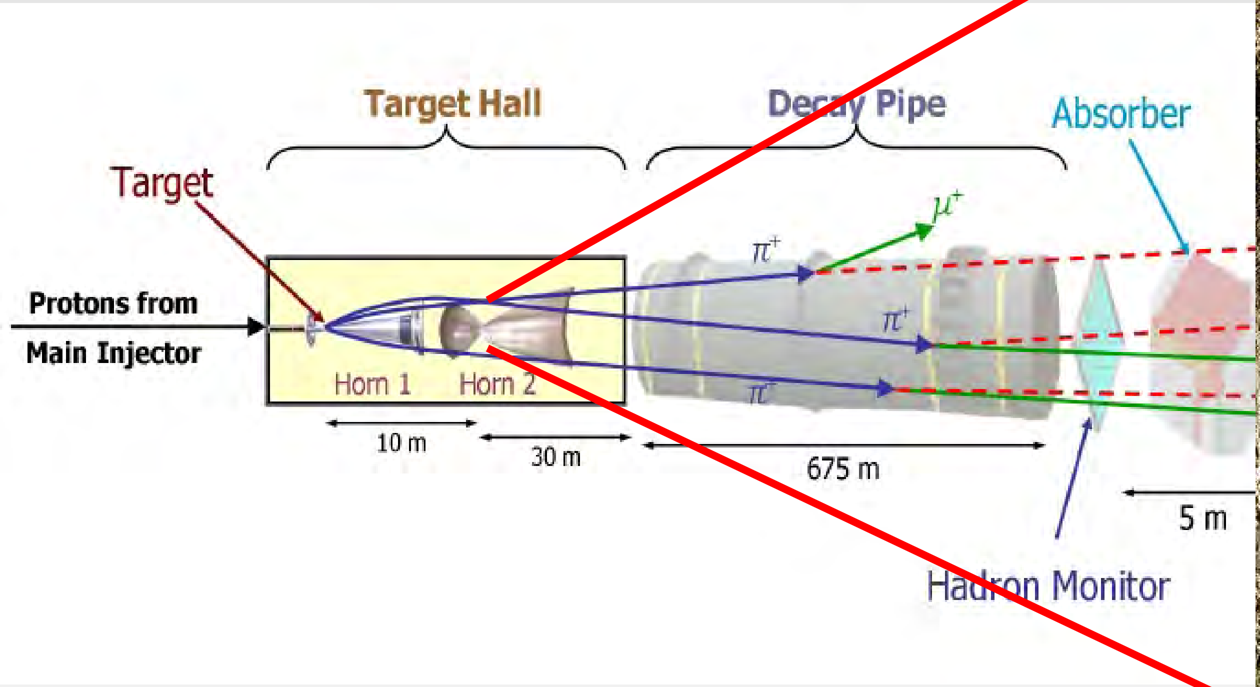


  - Dump proton beam on target → high-E pions
  - Charge-select and focus pions in magnetic ”horn”
  - Pions decay in flight via $\pi^+ \to \mu^+ + \nu_\mu$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

MINOS @ Fermilab

- "Main Injector Neutrino Oscilla



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$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

… 735 km later

Physics goals

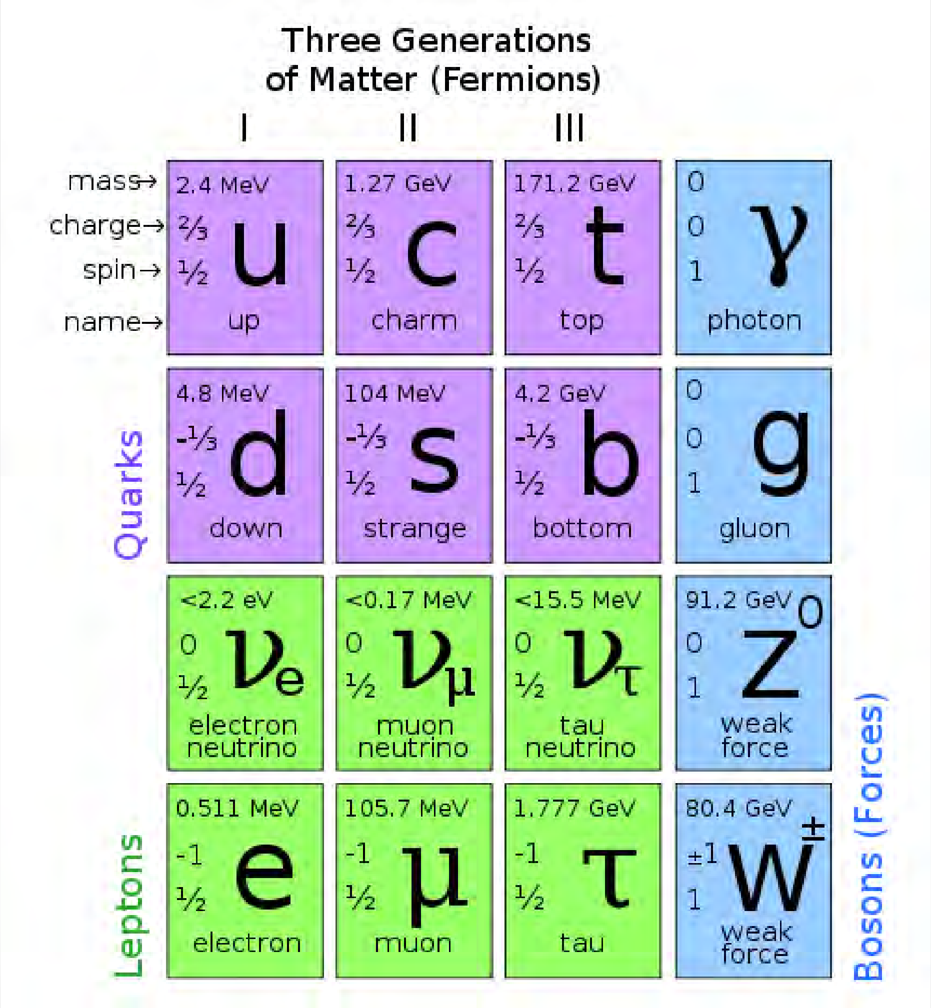
- Precision study of $\nu_\mu \to \nu_\mu$ disappearance
  - Hunt for $\nu_\mu \to \nu_e$ oscillations

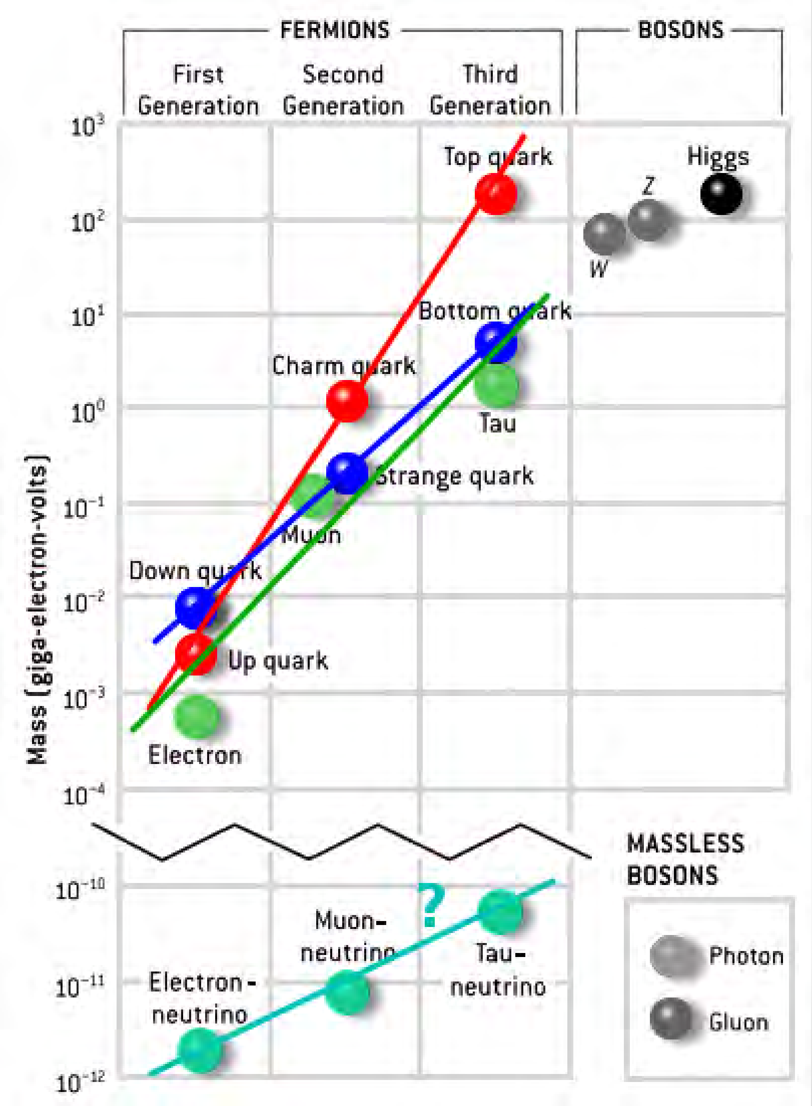
Minos far detector:

- Loacted in Soudan mine, MN
- 5.4 kt magnetized iron / solid scintillator
- neutrino interactions produce scintillation light

Why precision measurements?

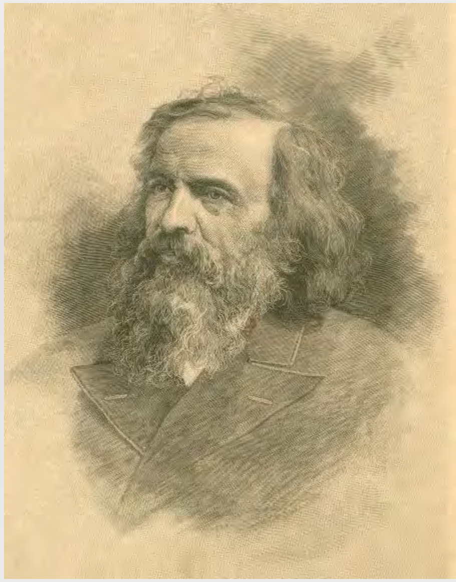
- We see a lot of unexplained structure in the Standard Model





The Periodic Table in 1870

I	II	III	IV	V	VI	VII	VIII		
H 1.01									
Li 6.94	Be 9.01	B 10.8	C 12.0	N 14.0	O 16.0	F 19.0			
Na 23.0	Mg 24.3	Al 27.0	Si 28.1	P 31.0	S 32.1	Cl 35.5			
K 39.1 Cu 63.5	Ca 40.1 Zn 65.4		Ti 47.9	V 50.9 As 74.9	Cr 52.0 Se 79.0	Mn 54.9 Br 79.9	Fe 55.9	Co 58.9	Ni 58.7
Rb 85.5 Ag 108	Sr 87.6 Cd 112	Y 88.9 In 115	Zr 91.2 Sn 119	Nb 92.9 Sb 122	Mo 95.9 Te 128	I 127	Ru 101	Rh 103	Pd 106
Ce 133 Au 197	Ba 137 Hg 201	La 139 Ti 204	Pb 207	Ta 181 Bi 209	W 184		Os 194	Ir 192	Pt 195
			Th 232		U 238				



Dmitri Mendeleev
1834 – 1907

Understanding flavor

- Something very fundamental may be hiding in the flavor structure of elementary particles
- Some theoretical ideas exist
- … all of them predict specific relations among particle masses and oscillation parameters
- To test if any of these relations is realized in nature, we need to measure masses and oscillation parameters as precisely as possible

Neutrinos faster than light?

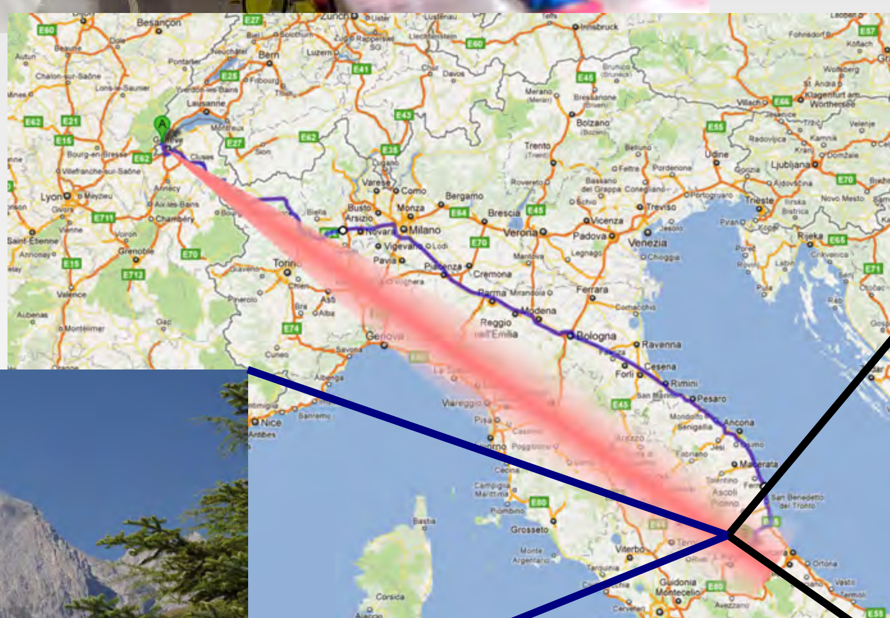
The OPERA experiment

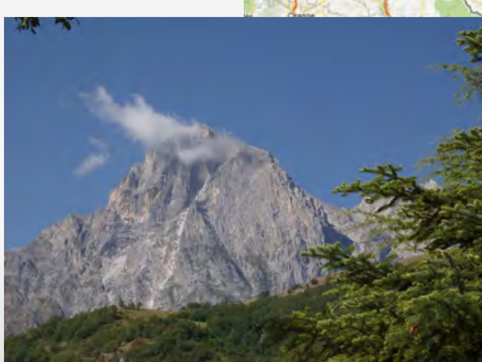
The CERN neutrino beam

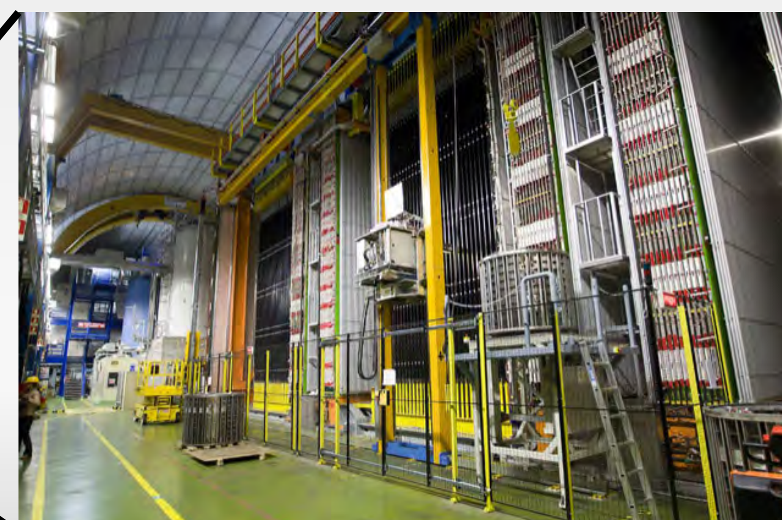
- Dump protons on target to produce high-energy pions
- Pions decay into neutrinos

OPERA detector:

- 1 250 tons of lead and photographics emulsion



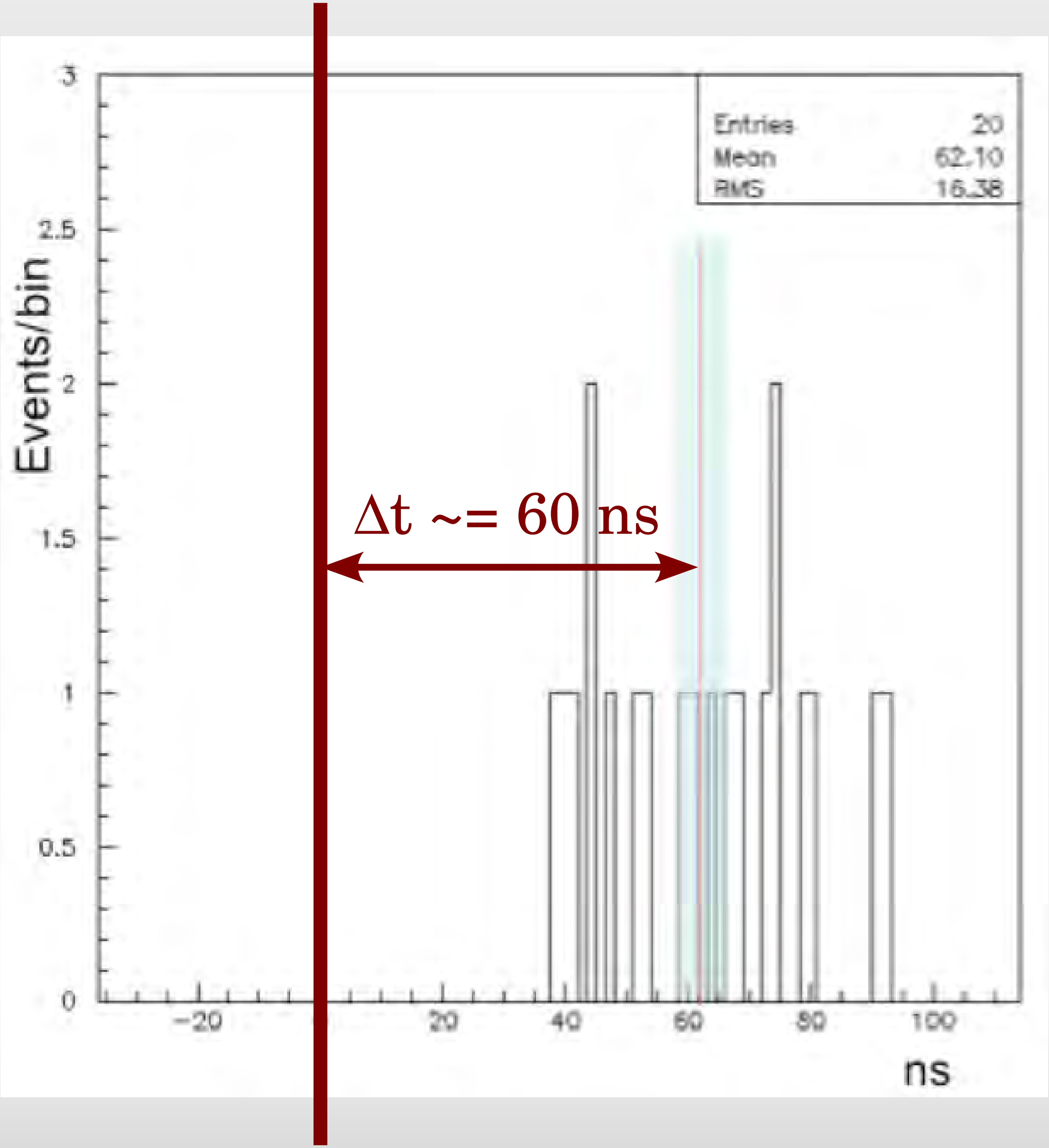


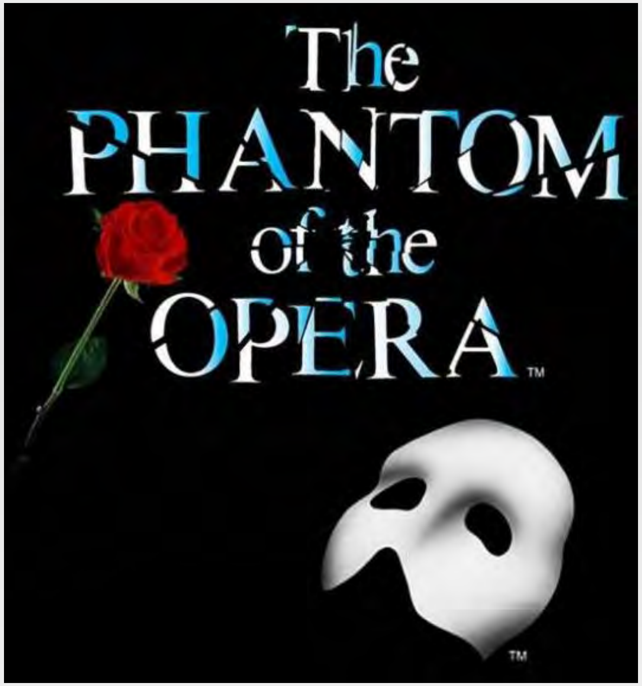


OPERA Timing

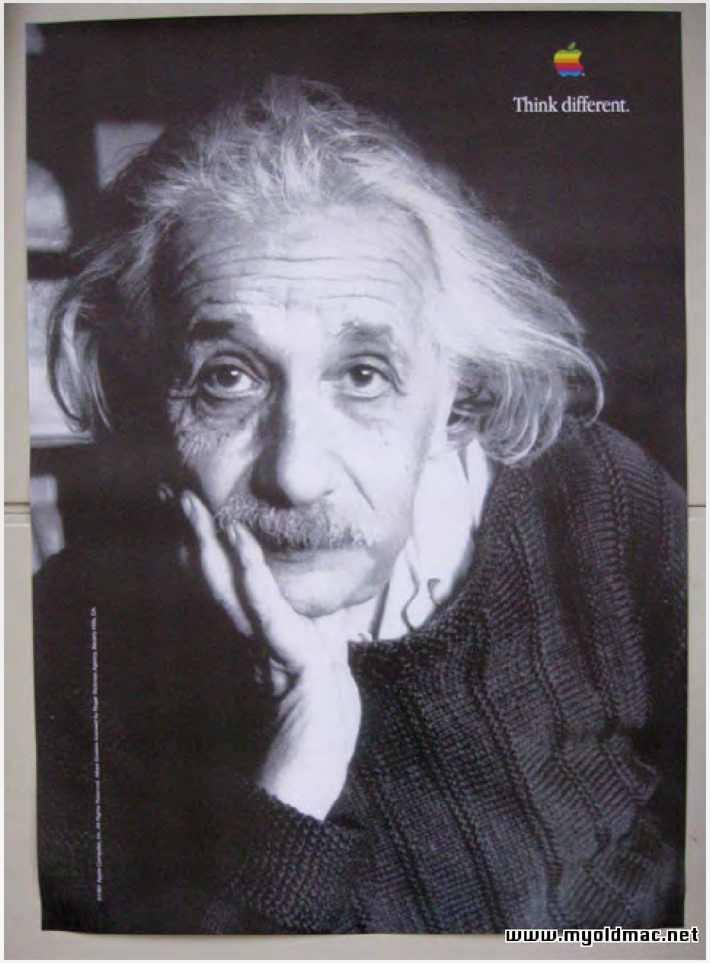
- GPS timing (nanosecond accuaracy)
- Neutrino production time:
  We know when the protons hit the target
- Neutrino detection time:
  Detection of scintillation light produced by neutrino's interaction products can be timed to nanosecond accuracy
- Distance from CERN to Gran Sasso:
  known to with ~20 cm (= 0.7 ns)

The phantom of the OPERA





What does this mean?



What does this mean?

About 210 scientific articles on the OPERA result written already!

- Did OPERA make a mistake?
- Is the theory of relativity (and, in consequence, much of modern physics) just wrong?
- Is the maximum allowed speed different from the speed of light?

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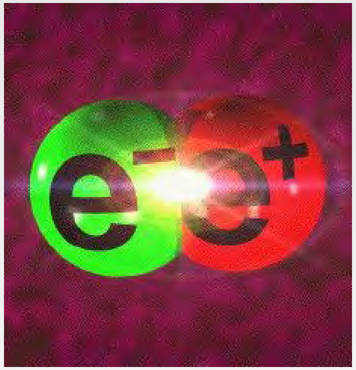
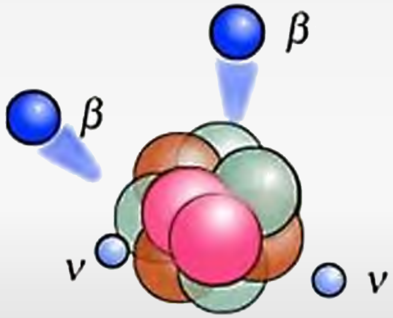
What comes next?

The future

- Pauli's ”invisible particles” are no longer invisible
- They are tools of high-precision physics
- They teach us about
  - particle physics
  - nuclear physics
  - astrophysics
  - cosmology







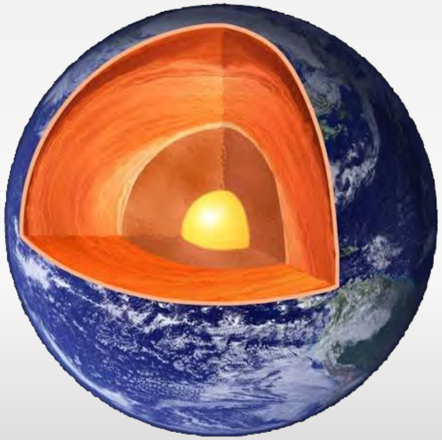
The future

Many open questions:

- Are neutrinos faster than light?
  - Expect answer soon (from MINOS and others)
- Are there more than three neutrino species?
  - Many inconclusive hints ...
- How do neutrinos get such tiny masses?

Practical applications?

- Monitoring nuclear reactors
  - Neutrinos provide unintrusive tool to monitor a reactor from a distance
  - Especially interesting for non-proliferation of nuclear material

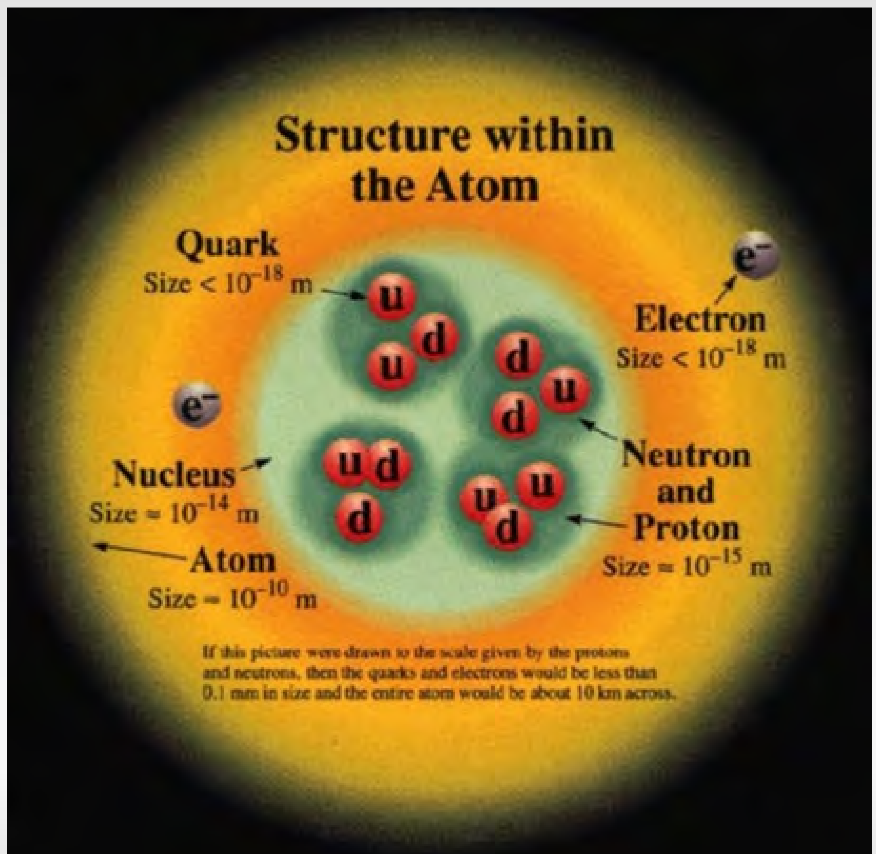


- Studying the interior of the Earth
  - Neutrino emission from radioactive decays inside the Earth
  - Density measurements

Welcome to the ν world!

The structure of matter

Protons and neutrons, in turn, consist of quarks.



A bit of quantum mechanics

A bit of quantum mechanics

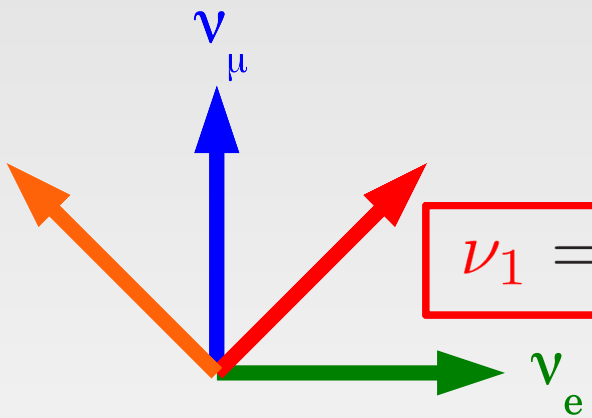
A bit of quantum mechanics

- In QM, every particle is described by a vector (can be visualized as an arrow)
- E.g.: Electron neutrino: Horizontal arrow
  Muon neutrino: Vertical arrow

A bit of quantum mechanics

- A particle can be in several states *simultaneously*

$$\nu_2 = -\nu_e + \nu_\mu$$



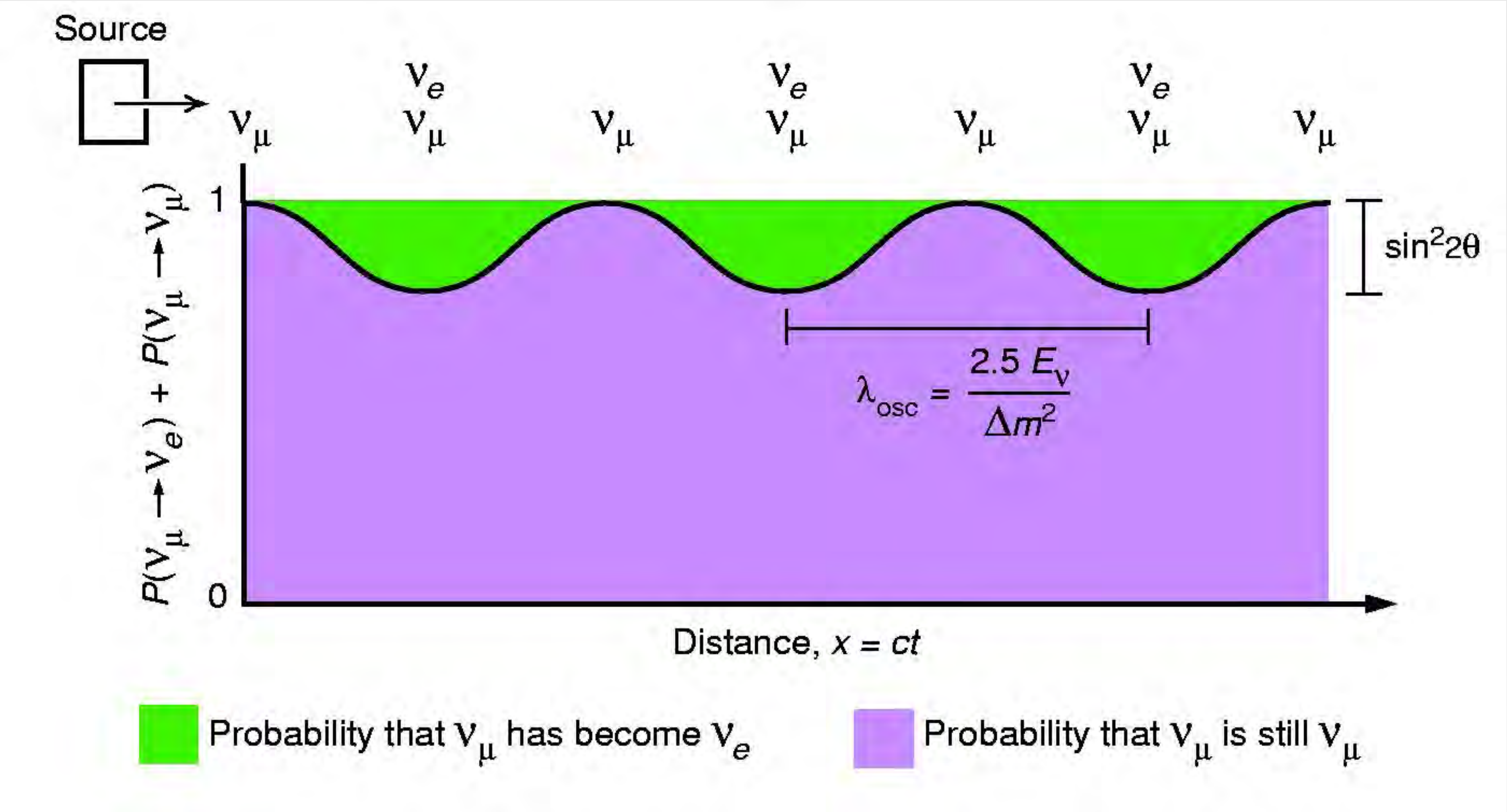
$$\nu_1 = \nu_e + \nu_\mu$$

- ν_e, ν_μ: Detectable neutrino states (for instance $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$)
- ν_1, ν_2 States with well-defined mass & energy

A bit of quantum mechanics

- Propagation of particle through space and time = Oscillation of its state vector
  (Analogy: Electromagnetic wave
  = oscillation of electric field vector)
- States of different energy (ν_1, ν_2) have different oscillation frequencies
- After a while, ν_e is converted to ν_μ!

Neutrino oscillations



OPERA Timing