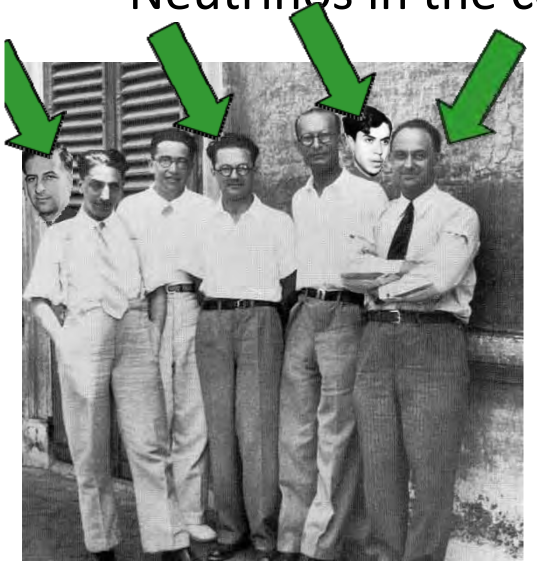
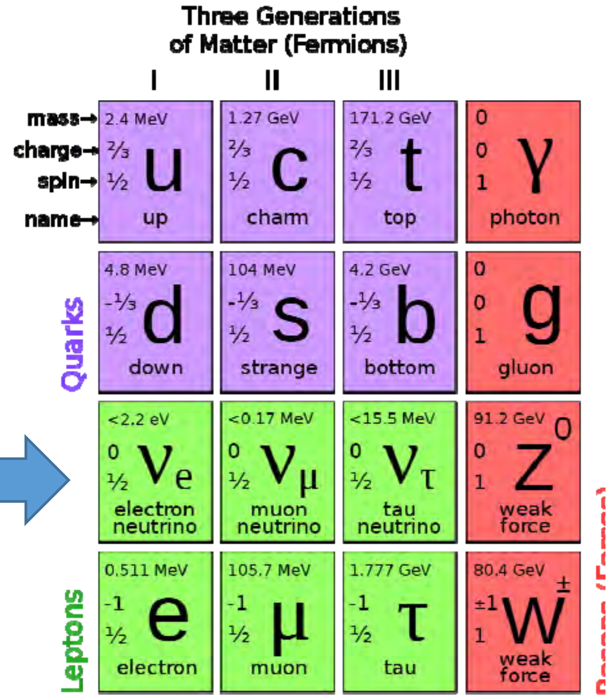
An introduction to Neutrinos in Physics and Astroph

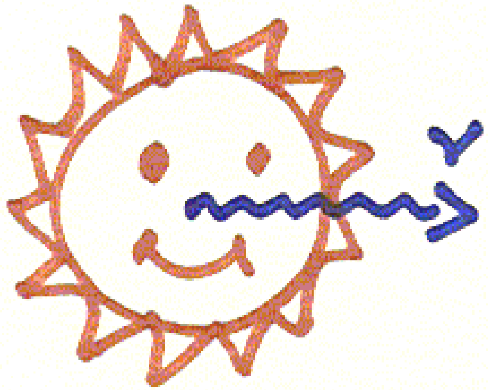
- Identity card of the neutrino
- Neutrino properties and puzzles
- What has been learnt about neutrinos?
- What you can be learny from neutrinos ? Neutrinos to watch the sky
- The energy source of the Sun
- Go underground to see the stars : The Gran Sasso
- Neutrinos in the cosmos ...

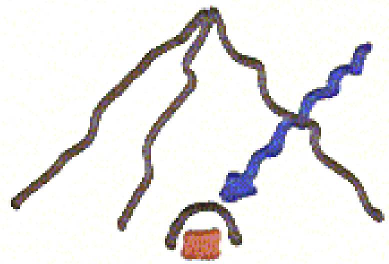




Neutrino identity card

- Particle associated with a type of radiation
- Birth (of the concept) : 1930
- Maternity / Paternity : Pauli , Fermi
- Family : Amaldi , Maiorana , Pontecorvo
- Residence: almost everywhere
- Origin : interior of the Earth , the Sun and stars , nuclear reactors , particle accelerators ...
- Distinguishing features : Extremely elusive (penetrating)
- Mass : " very small " compared to that of other particles
- Family state: the family includes three types

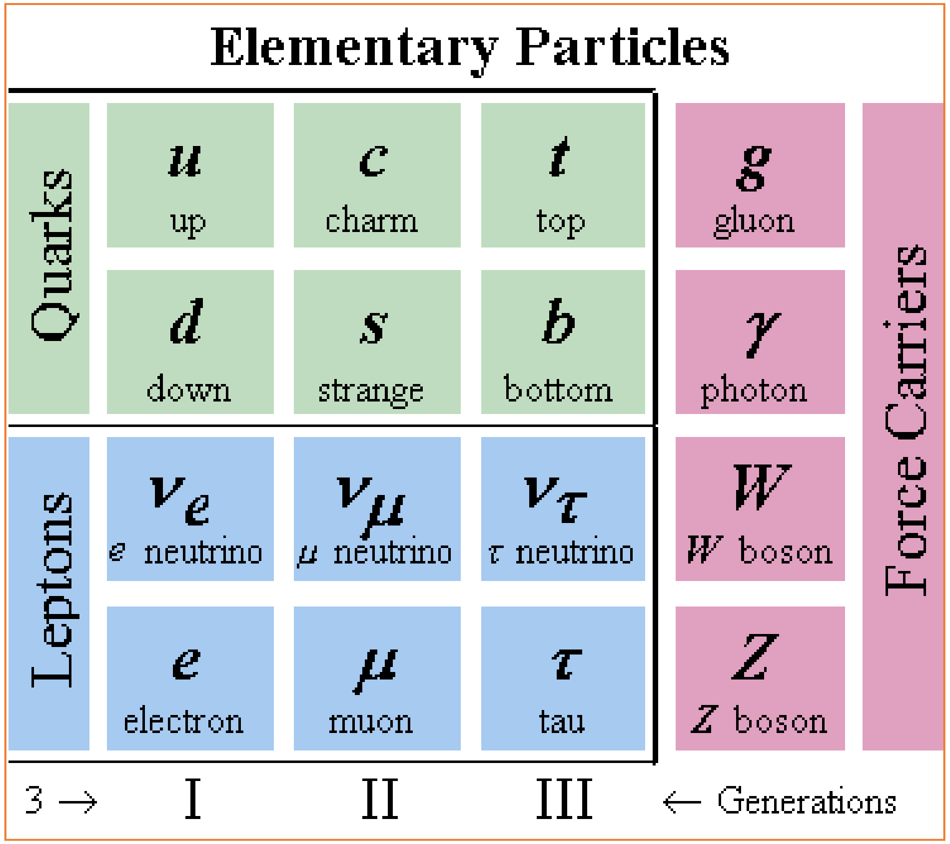




$m < 10^{-6}\, m_e$

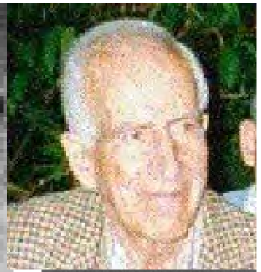
Neutrino properties, summary

- Neutrinos are particles which have only electro-weak and gravitational interactions;
- they are leptons with no electric charge and spin ½
- We know three types (flavours) of neutrinos, each connected with a charged lepton.
- We define neutrino with electron flavour a particle which is produced in β+ decays togheter with positrons, and the same for the other types.
- Each neutrino has a corresponding antineutrino which has opposed leptonic family number and global lepton number.
- The three neutrinos, in doublets with the corresponding charged leptonss complete the three families (or generations), similar to the three doublets which constitute the three families of quarks



A short history of the neutrinos





1898 Discovery of the radioactivity
1926 Problem with beta radioactivity
1930 Pauli invents the neutrino particle
1932 Fermi baptizes the neutrino and builds the theory of weak int.
1946 Pontecorvo program of neutrino detection
1956 First observation of the neutrino by an experiment

1957 Pontecorvo: hypothesis of neutrino oscillations
1962 Discovery of a second type of neutrino: n_{μ}

1970 Davis experiment opens the solar neutrino puzzle

1974 Discovery of neutral currents thanks to the neutrinos

1987 Neutrinos from SN 1987A

1991 LEP experiments show that there are only three light neutrinos
1992 Missing solar neutrinos confirmed by GALLEX

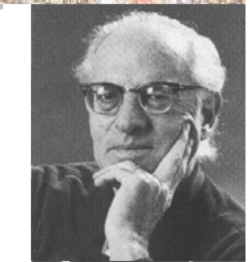
2001 SNO closes the solar neutrino puzzles, by directly proving the transformation of solar neutrinos

2002 Kamland observes transmutation of man made (reactor) neutrinos

2009 Borexino at GS detects geo-neutrinos

2010 OPERA at GS detects transformation ν_{μ} -> ν_{τ}

2015 Nobel prize for neutrino oscillations




The origins

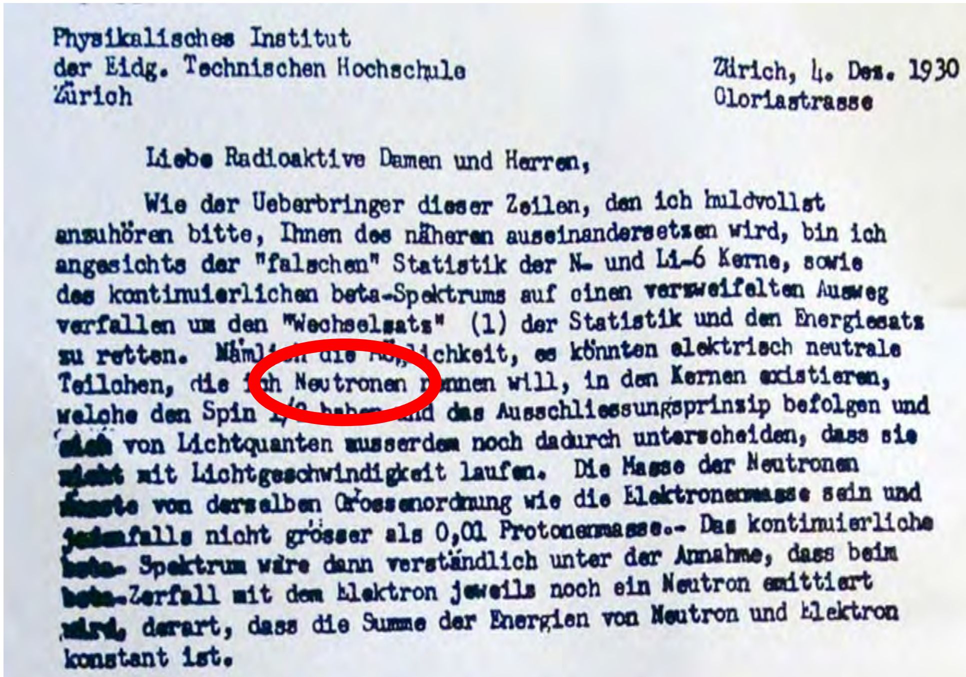
- In nuclear beta decay

  X-> X'+ e

energy in the final state seemed smaller than that of the initial state.

- In order to mantain energy conservation, in 1930 W. Pauli formulated the hypothesis of an invisible particle that is capable of carrying arbitrary amounts of energy and momentum, without being detected

  X-> X'+ e + ν_e



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

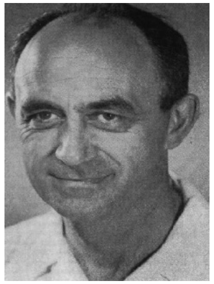
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

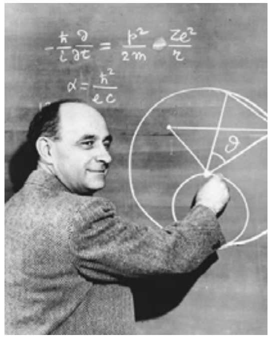
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Näml[illegible]lichkeit, es könnten elektrisch neutrale Teilchen, die [illegible]ch Neutronen [illegible]nnen will, in den Kernen existieren, welche den Spin [illegible] und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

- Since it is invisible , it must be electrically neutral.
- Since it can carry minimal amount of energy , its mass must be minimal (compared to those of other nuclear particles)

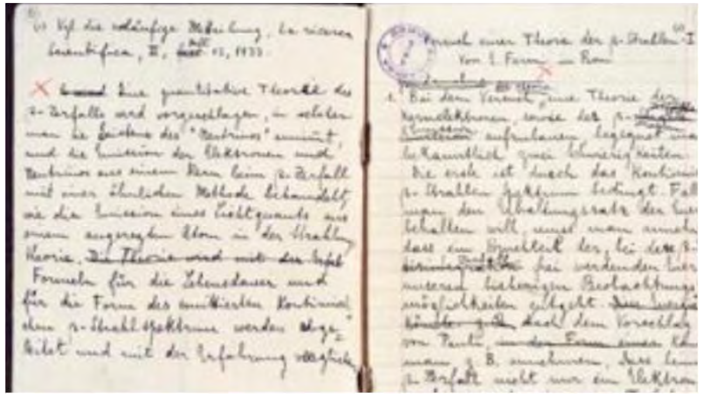
The baptism : neutrons or neutrinos ?



- Pauli called neutron the hypothetical particle.
- In the same years Chadwick discovered the neutron, one of the nucleus components , weighing about the same as the proton but electrically neutral.
- The Chadwick neutron was **heavy**, differently from the **light** particle postulated by Pauli .
- In a discussion with Fermi , Edoardo Amaldi invented the name neutrino , with the typical Italian diminutive suffix,
- Fermi spread the name in the scientific community



How do neutrinos interact?

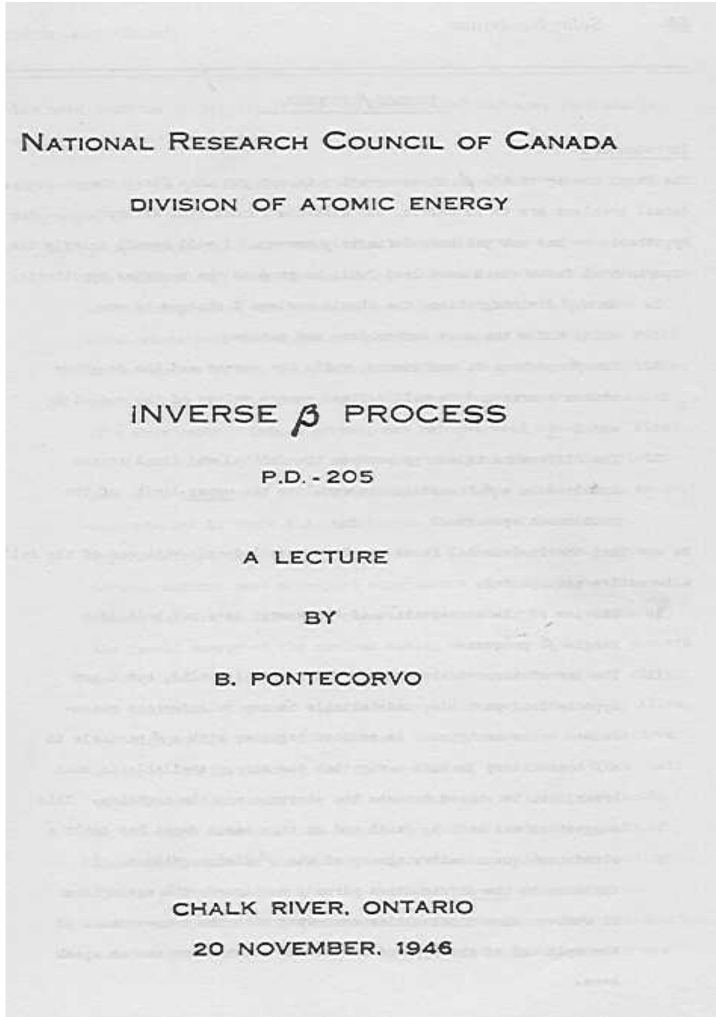


- Fermi formulated the first quantic and quantitative theory of neutrino interactions .
- It is still valid today for the description of low-energy neutrino interactions (E << M (W)) 8
- It is the limit of the Standard model for low energies
- Even today, the Fermi Theory is the paradigm for the construction of new theories of hypothetical interactions , in the limit of energy smaller than the relevant scale

(The article written by Fermi was rejected by the prestigious journal Nature ...)

The program of Bruno Pontecorvo:

- What are the neutrino sources?
- How can neutrinos be detected?



NATIONAL RESEARCH COUNCIL OF CANADA

DIVISION OF ATOMIC ENERGY

INVERSE β PROCESS

P.D. - 205

A LECTURE

BY

B. PONTECORVO

CHALK RIVER, ONTARIO

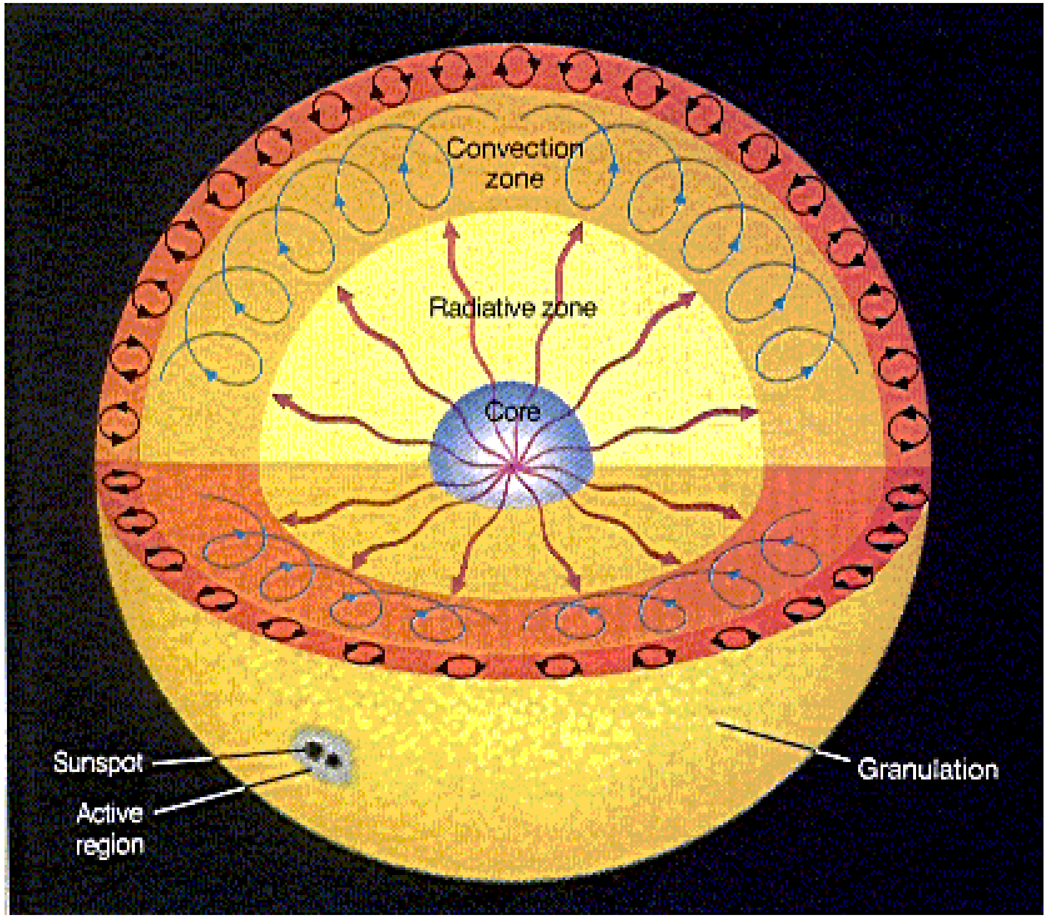
20 NOVEMBER, 1946

Solar neutrinos

- If in the Sun heat is generated by transforming H into He, any such fusion reaction has to produce two neutrinos:

$4\ H \to He + heat + 2e + 2\ \nu_e$

- This is simply a consequence of the conservation of electric charge and (family) lepton number



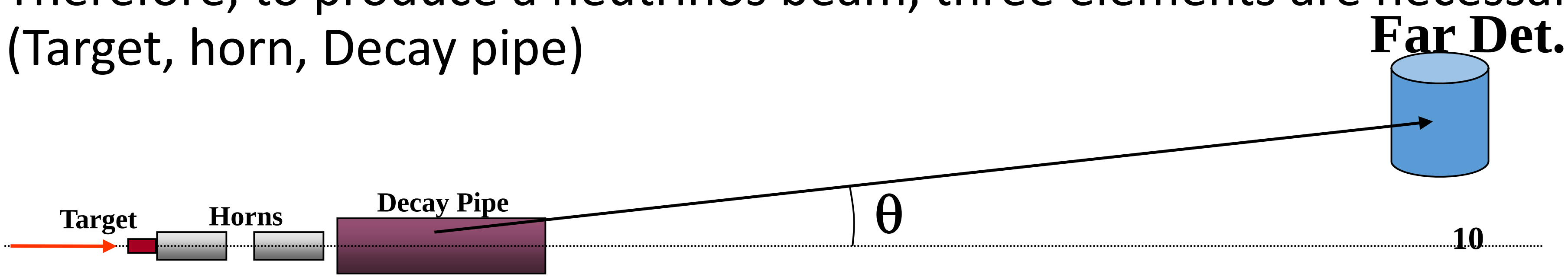
The Sun is a powerful neutrino source, sending us a flux of about 10^{11} neutrino/cm^2/s

Neutrinos beams from accelerators

- Since the 60-70's, we can extract neutrinos beam, principly muonic neutrinos.
- A proton beam impinges onto a target where pions are abundantly produced by strong interaction.
- Charged pions are focused by means of a magnetic horn and afterwards, they enter a "decay pipe" where decay occurs.
- The principal decay mode is

  $\pi^+ \to \mu^+ + \nu_\mu$

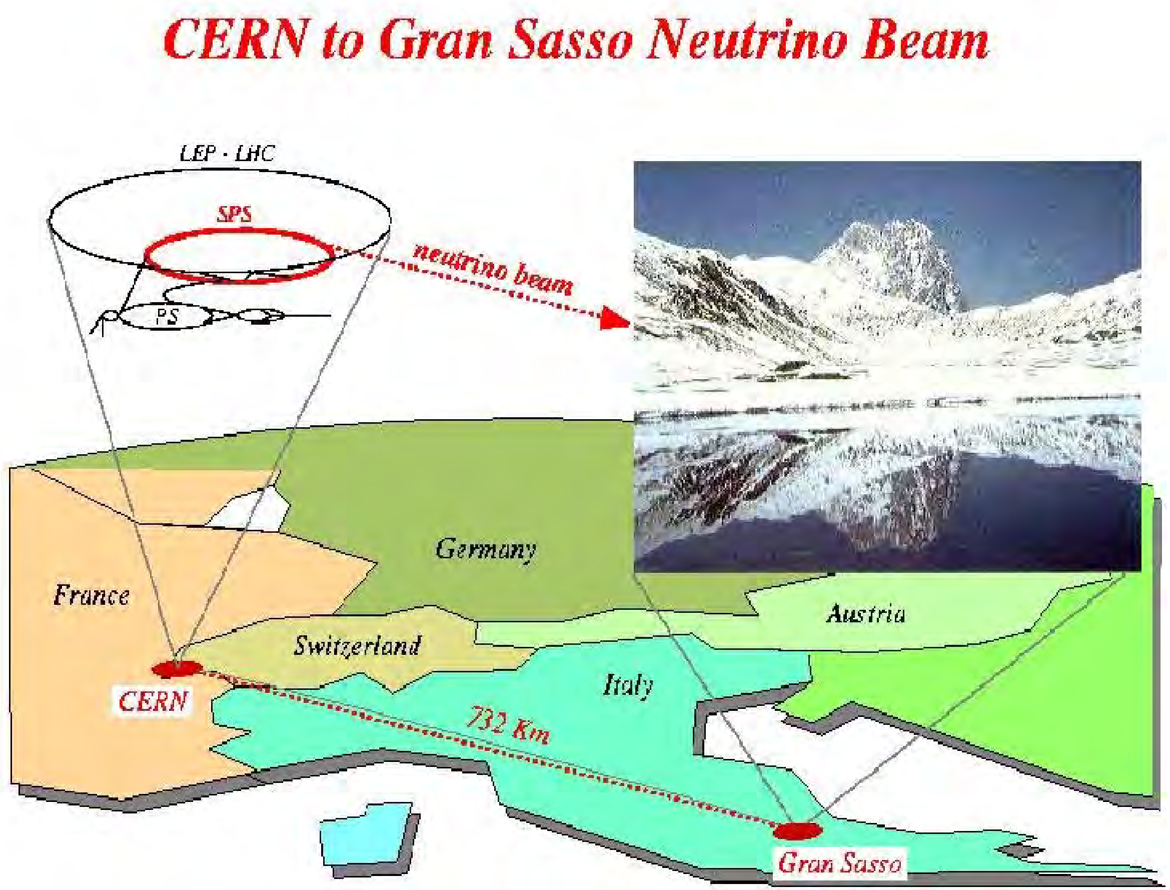
  and similarly for π^-
- At the end of decay pipe, muons are stopped in cement block, and only neutrinos are left.
- Therefore, to produce a neutrinos beam, three elements are necessary (Target, horn, Decay pipe)



From CERN to Gran Sasso

- Shoot neutrinos produced at CERN in Geneva under the earth's crust to 732 Km

- Muonic neutrinos can transform into other any other kind of neutrino



OPERA experiment succeded to detect ν_μ -> ν_τ

Artificial sources of (anti)neutrinos: nuclear reactors

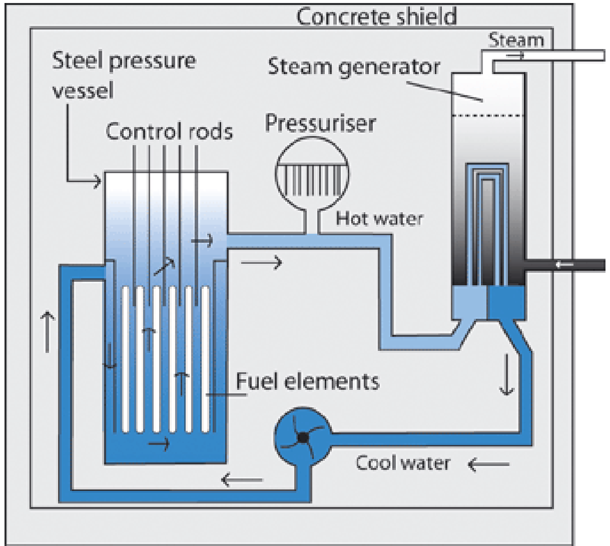
- **Typical commercial reactors have thermal powers of 3GW and burn uranium ^{235}U**
- **On average every nuclear fission produces Δ=200MeV and a typical reactor produces 10^{20} fis/s**
- **One can understand that the average number of neutrinos per fission is 6 . Indeed in the neutron induced fission ,**

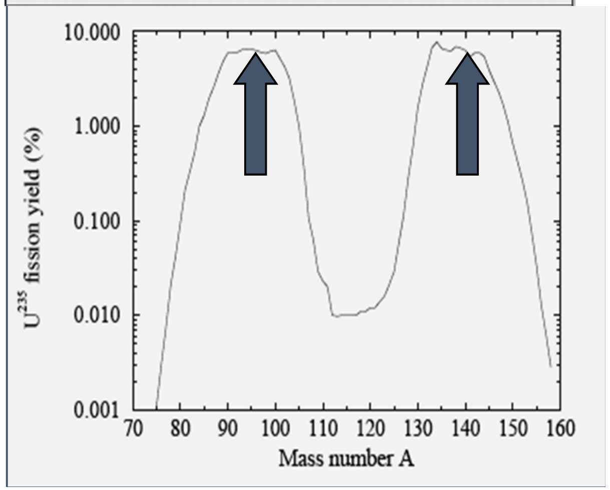
$$_{92}U^{235} + n \rightarrow X1 + X2 + 2n$$

the distribution of fission products has a peak around A= 94 e A =140; for these mass number stables nuclei are $_{40}Zr^{94}$ e $_{58}Ce^{140}$. To reach these nuclei with total charge 40+58=98, starting from 92, 6 protons must be trasformed into neutrons, so we need 6 beta decays, with 6 antineutrinos.

- **Therefore a reactor with thermal power of 3GW produce isotropically $L_\nu \approx 6 \times 10^{20}$ anti ν/s.**
- **The flux at 10 m is**

$$\Phi = 5\ 10^{13} \text{ anti } \nu \text{ /cm}^2\text{/s}$$





β inverse process and the antineutrinos detection

- The detection of antineutrinos, i.e. the products of their interactions, was performed for the first time in 1956, observing a process that is essentially the inverse of the neutron β decay and still is the classic way to study these particles

  (1) anti-ν_e + p $\rightarrow$ n + e^+

- The positron, the light particle in the final state, brings with it (almost) all the available energy, its kinetic energy being $T_e=E_\nu + m_p - m_n - m_e = E_\nu - 1.8MeV$

  The process is therefore possible for antineutrinos with $E_\nu > 1.8MeV$.

- In the target, the positron slows down and annihilates on an electron,

  (2) $e^+ + e^- \rightarrow 2\gamma$

  this provides a first signal two photons in opposite directions and each with $E=m_e$

- The neutron is slowed down to thermal energies (in time Δt of the order of tens of μs in a liquid). If the target , ^AZ, is an absorber of neutrons, the neutron can be identified by the γ emitted by the capture:

  (3) $n + {}^AZ \rightarrow {}^{A+1}Z + \gamma$.

- The presence of this signal, delayed with respect to annihilation, is a distinctive feature of the interaction of antineutrinos: we have lots of background counts (due to cosmic and / or natural radioactivity) corresponding to (2) or (3), but a lot less if we require both (2) and (3).

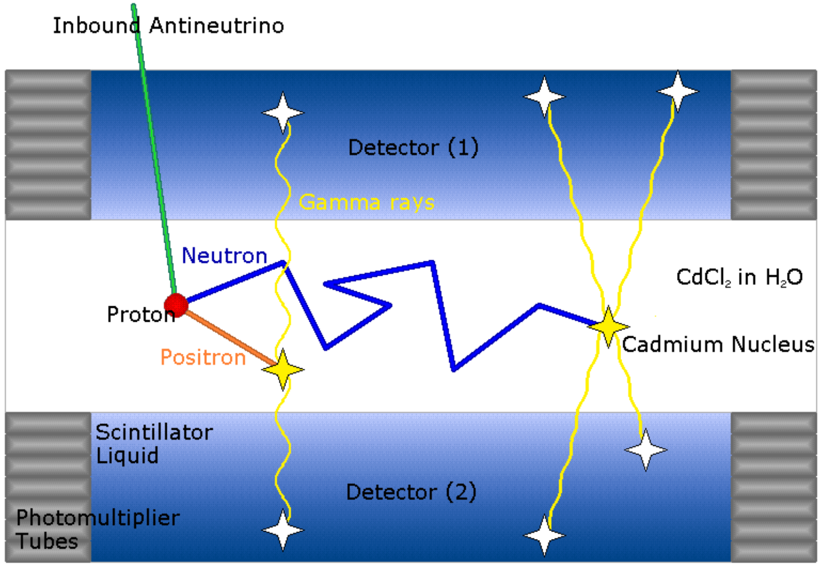
Reines and Cowan experiment

- As a source of anti- ν_e they used a nuclar fission reactor, where - on average - six anti-ν_e for each fission are produced. The energy spectrum is continuous, with a maximum around 5 MeV. Outside the core of a power reactor there are neutrino fluxes of order

  $\Phi \approx 10^{13}$ cm^{-2} s^{-1}.

- The target contained 200 liters of water with $\approx 10^{28}$ "free"protons.
- A cadmium salt was dissolved in water. Cadium is a nucleus with large cross section for neutron capture, so one can detect neutrons using (3)
- The target was surrounded by liquid scintillator which was coupled with photomultipliers in order to detect γ from annihilation (2) and from capture (3).
- The detector was located about a dozen meters from the reactor core and **a dozen metres underground,** to get a screen from cosmic rays

1) anti-ν_e + p -> n + e^+
2) e^+ + e^- > 2 γ
3) n+ ^AZ -> ^{A+1}Z + γ



- Reines and Cowan, selected the events which featured both (2) that (3).

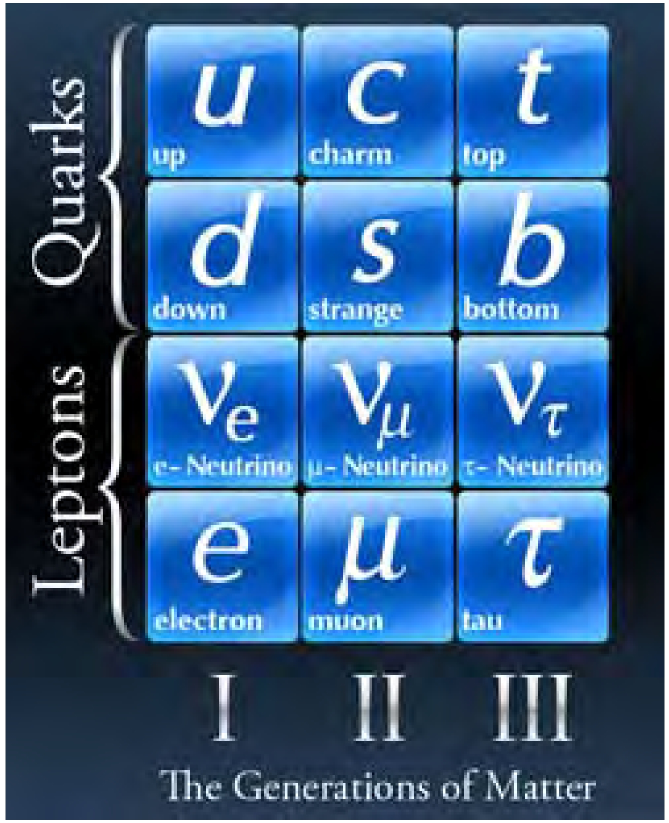
•Till now, the principle of the detection is still the one used by Reines and Cowan, in their pioneer experiment.

The puzzle of neutrino metamorphosis (neutrino oscillations)

•Already in 1957 Pontecorvo had formulated the hypothesis that neutrinos of one type could be transformed spontaneously in the other

•Since 1970 we have had evidence of this happening

•Since 2001 we have proof , indeed more than one proof...



The Nobel Prize in Physics 2015

Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

Photo: A. Mahmoud

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Oscillations of solar neutrinos

SNO experiment (Sudbury Neutrino Observatory) in Canada has shown that a fraction of the electron neutrinos emitted by the sun during their journey transform into other particles

- SNO detects the flux of ν_e, as well as the total flux of neutrinos cominf from the Sun ($\nu_e + \nu_\mu + \nu_\tau$)
- SNO has shown that the Sun produces as many neutrinos as predicted by theory , but a fraction of the neutrinos change type during the Sun-Earth journey

Oscillation of atmospheric neutrinos

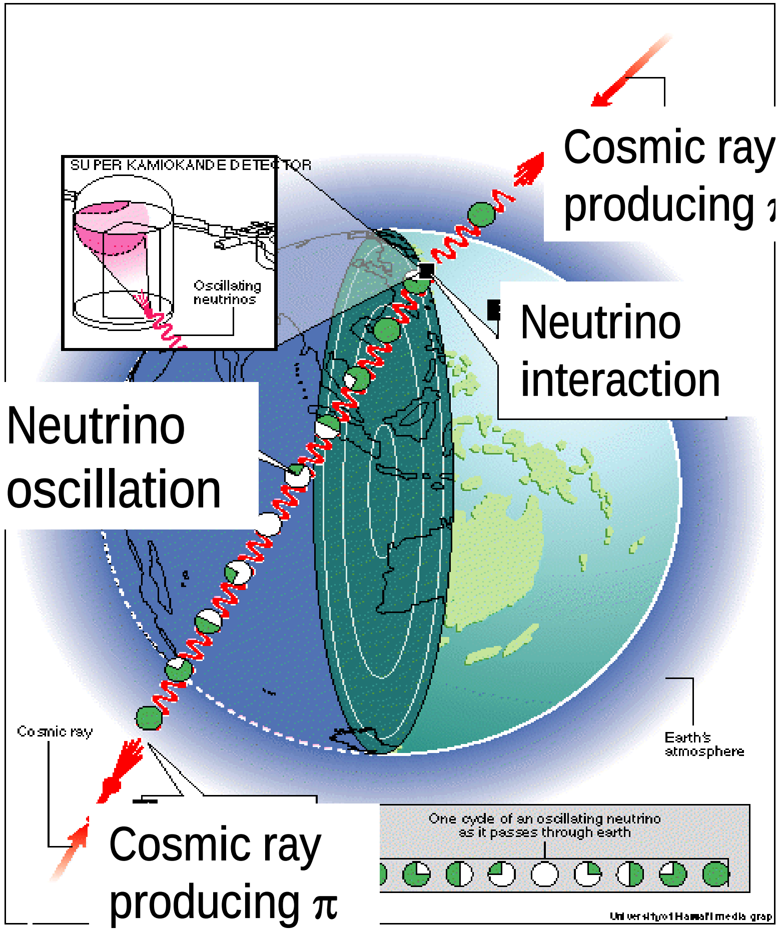
- By the interaction of the primary cosmic rays (p , α) with atmospheric nuclei pions are produced and these decay into muon and electron neutrinos

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + anti\ \nu_\mu$$

- One expects that the number of muon-like events is twice the number of " electron-like events

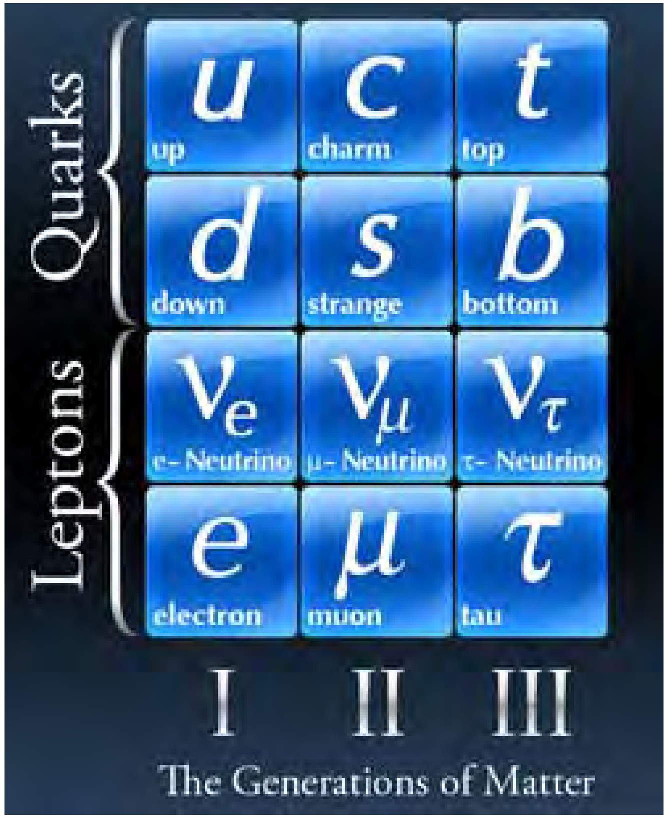
$$R = ev(\mu)/ev(e) = 2$$



- The experiment shows that R = 2 for neutrinos arriving from above , while R = 1 for those that come from below, ie passing through the earth neutrinos have undergone a metamorphosis

The puzzle of families

- There are three types of neutrino , each associated with a charged particle
- All the constituents of matter appear replicated three times (three generations)
- Why 3 ?
- The question is still unanswered , like 60 years ago when at the discovery of the muon Rabi said :
- " **Who ordererd that**? "

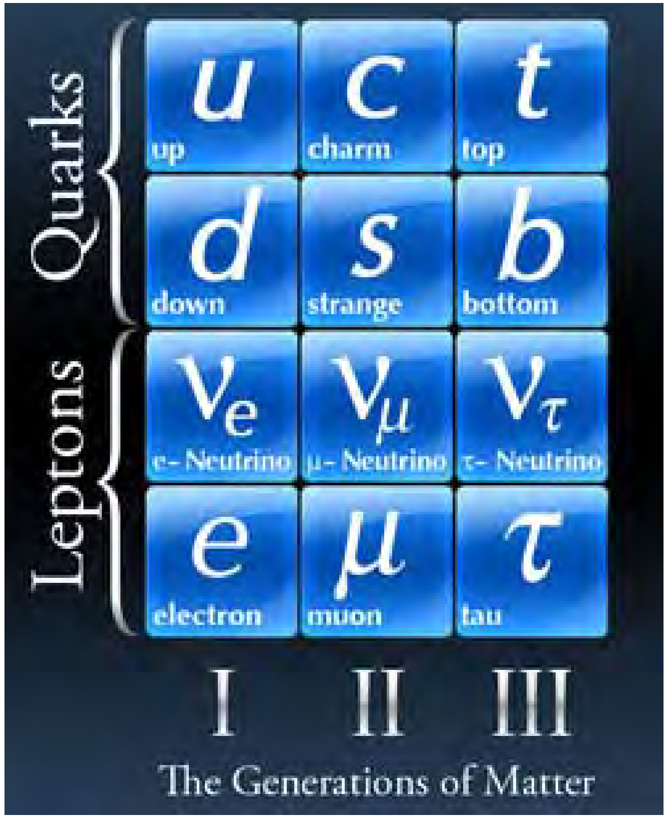


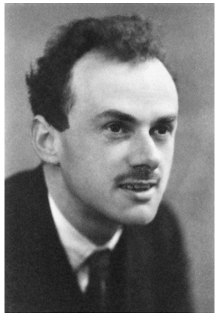
The puzzle of neutrino masses

•Masses of charged leptons are in the range from $1 m_e$ to $1000\ m_e$.

•Neutrino masse are smaller than $10^{-6}\ m_e$

Why ?





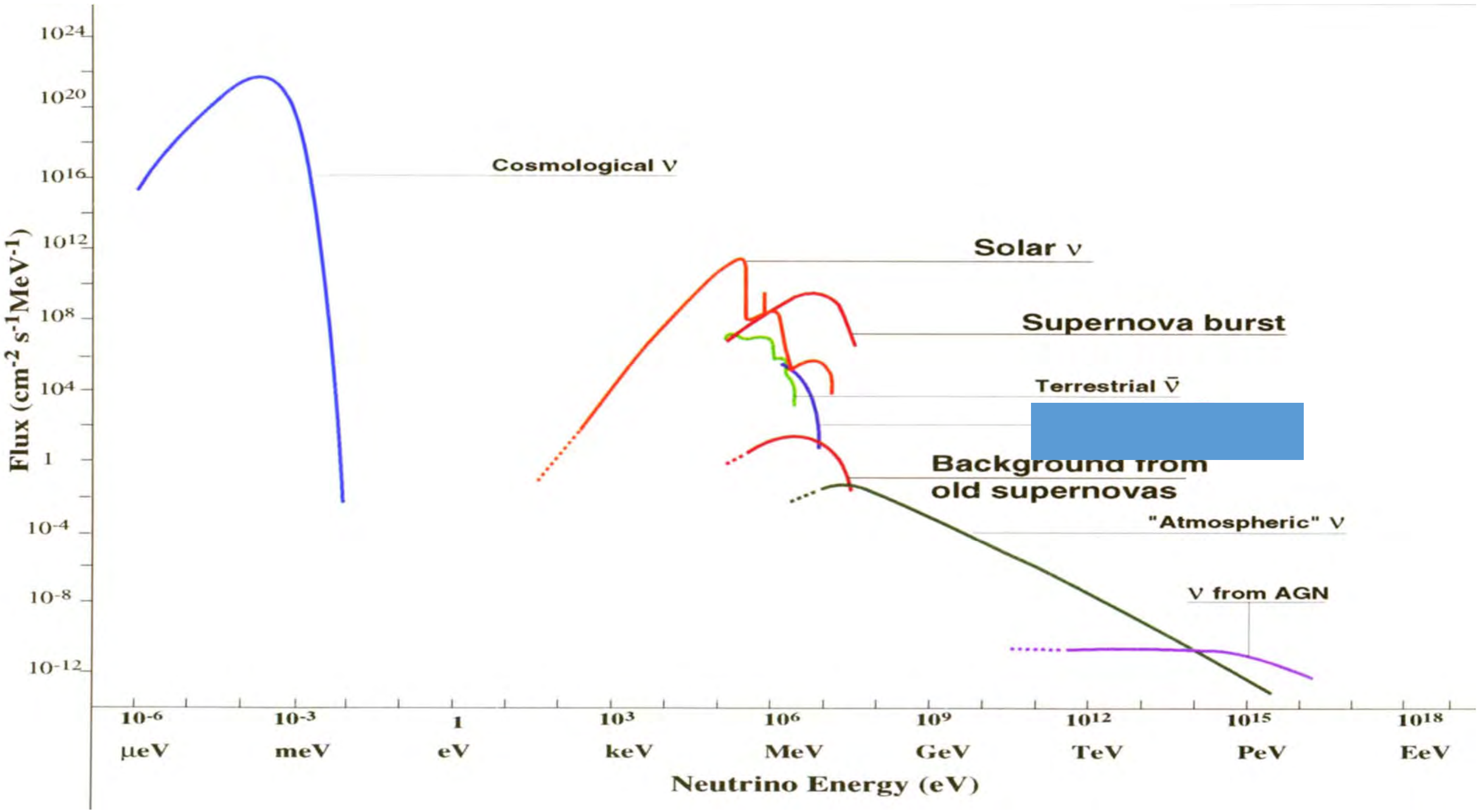
Neutrinos and antineutrinos: Dirac or Majorana

- According to Dirac's theory, to each particle is associated an antiparticle , " whose additive quantum numbers additives are opposite ")
- E.g. electron-positron , proton - antiproton , neutron - antineutron
- For neutral particles , particle and antiparticle may coincide , as demonstrated by E. Maiorana in 1937
- **Do Neutrinos coincide with their antiparticles** ?
- The question has extremely important implications (lepton number violation , matter antimatter asymmetry).
- Presently we do not have an experimental response. frontier research us performed across the world , including the laboratory of the Gran Sasso (exp . GERDA , CUORE, LUCIFER ...)

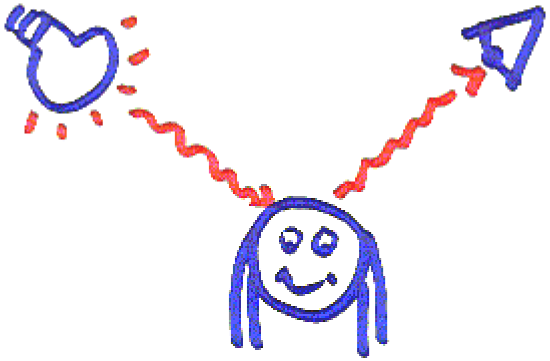
Neutrinos in Astrophysics
or
The Universe seen with neutrinos

- We know a lot about neutrino properties and interactions.
- In particular, we know what occurs during their propagation (oscillations)
- What can be learnt about the universe by using neutrinos as probes of astrophysical objects?

Natural neutrino sources



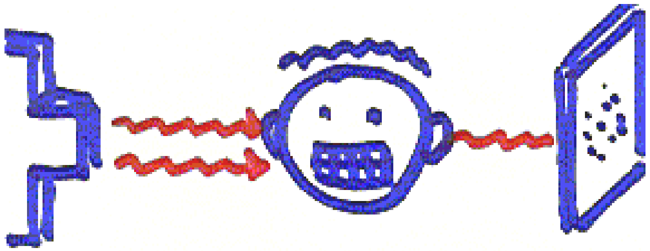
There are different ways of seeing: visible light



- Radiation source
- Interazione/target
- Detector (eye)

- (Remind the neutron well log..)

There are different ways of seeing: X- rays

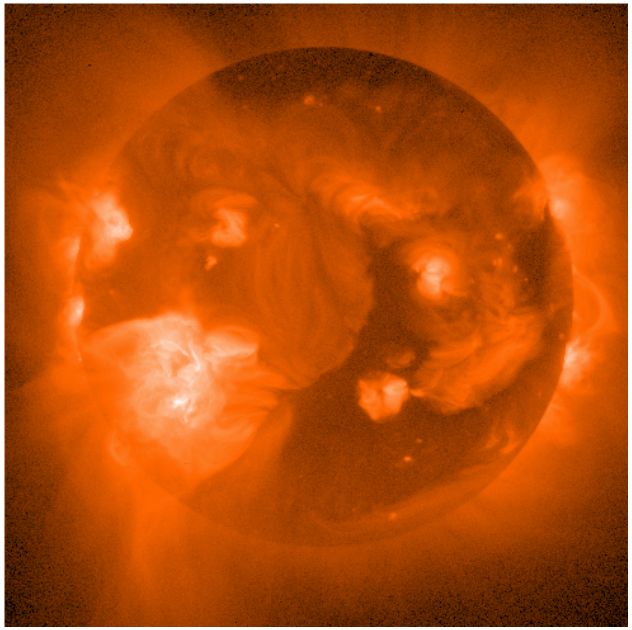


- For going deeper a more penetrating radiation is needed

- Still an e.m. radiation
- Detector is changed

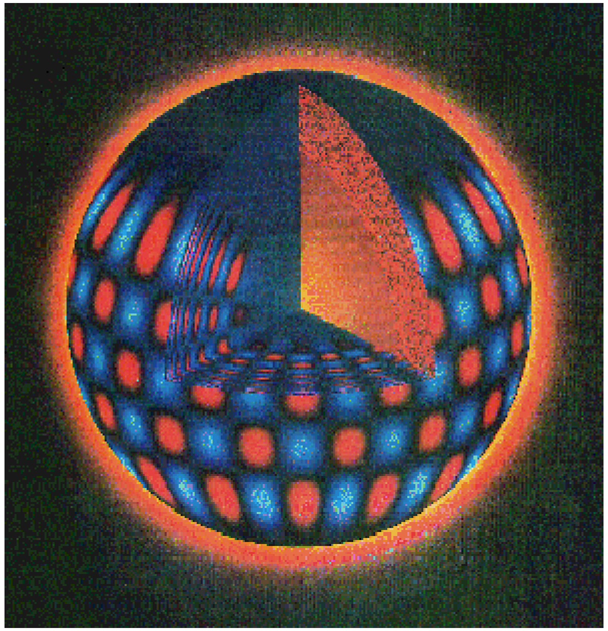
(eye-> photographic plate)

See the interior of stars (and planets)



- Stars produce all types of radiation : visible, infrared , ...

- To see inside them one needs much more penetrating radiation than X -rays



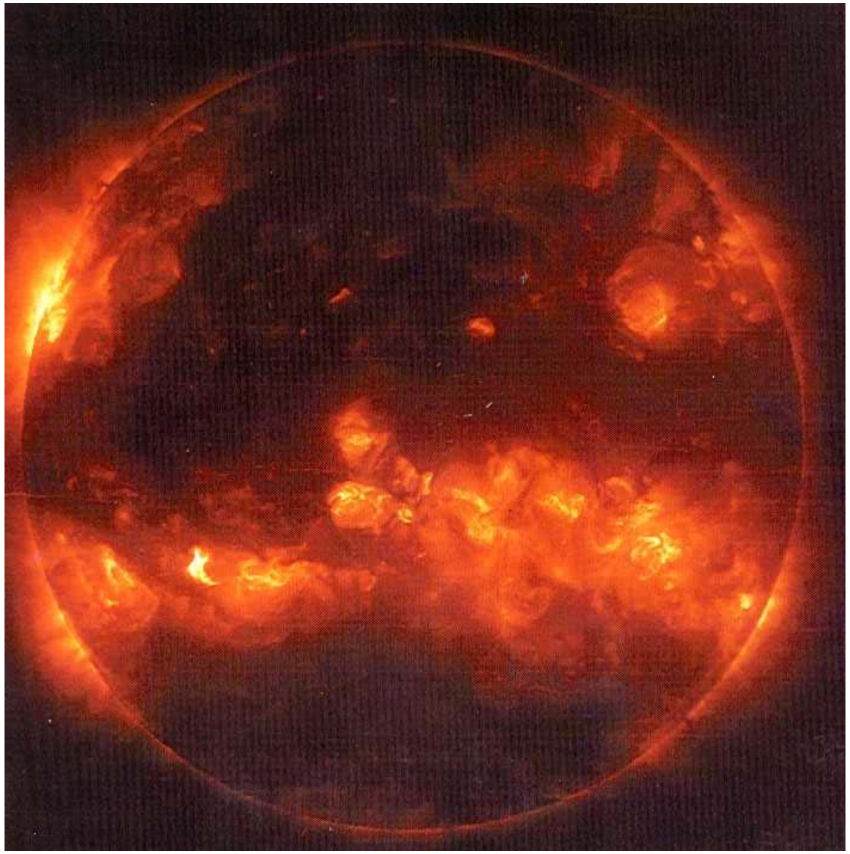
- To see the interior of Sun/Earth one can use :
  - acoustic waves (seismology)]
  - neutrinos

Why to look at the interior of stars ?

The Bedouin, the pastor , spent the night in the desert , which was completely dark. In order to help him, God , send his angels to puncture the black vault of the night with their spears. What we perceive as stars , they are just holes in the vault of the night from which we see the light that is beyond , in the paradise of God

(Legend of the Bedouin culture on the origin of the stars)

Stars energy source



•Kelvin ~1800: Gravitational energy can sustain sun's luminosity for nearly 30.000.000 years.

• It's too short to justify the evolution of biological and geological processes.

• Understanding the stars energy source was the scientific problem of the XIX century.

Which kind of energy source can sustain the sun for billion years?

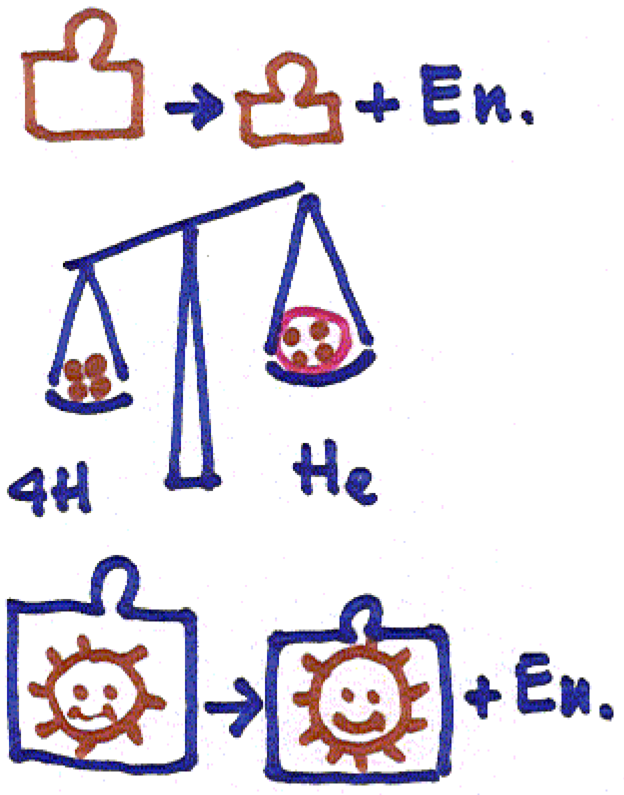
(see here ...)

Birth of nuclear astrophysics

Einstein (1905): **$E=mc^2$**

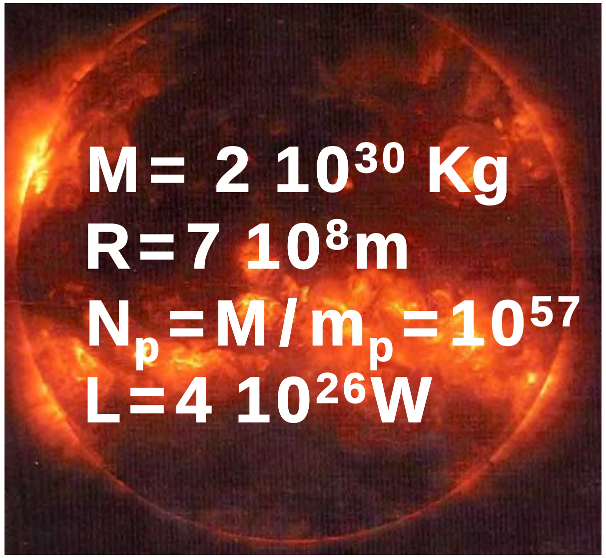
Aston (1918): **m(He) < 4 m(H)**

Eddington (1920): If a star initially consists of hydrogen, that gradually is transformed into heavier elements, then we understand the energy source of stars…and…*



*…If this is true, then we are closer to the dream of controlling this latent power, to the benefit of the human race or for its suicide (1920)

The Sun energy inventory



•It is easy to understand the dominant contribution to the solar energy production.

• The present luminosity $L=4\ 10^{26}$W can be sustained by an energy source U for a time t=U/L :

•a)chemistry: U» (0.1eV)N_p=1eV 10^{56} =2 10^{37}J -> $t_{ch}=2\ 10^{3}$ y

•b)gravitation U»GM ^{2}/R=4 10^{41}J -> $t_{gr}=3\ 10^{7}$ y

•c)nuclear U» (1MeV)N_p= 2 10^{54}J -> $t_{gr}= 2\ 10^{10}$ y

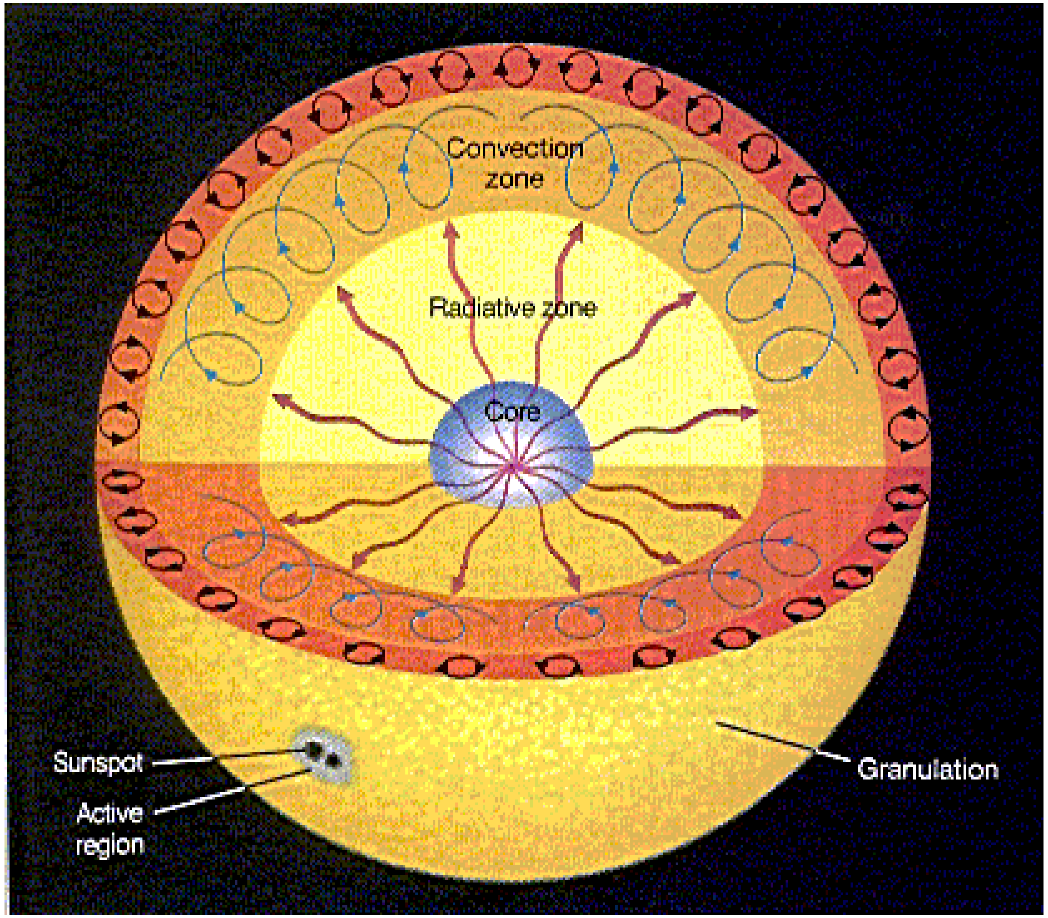
•Thus only nuclear energy can be important for sustaining the Solar luminosity over the sun age, $t=4.5\ 10^{9}$ y.

The proof ?

- If in the Sun heat is generated by transforming H into He, any such fusion reaction has to produce 2 neutrinos

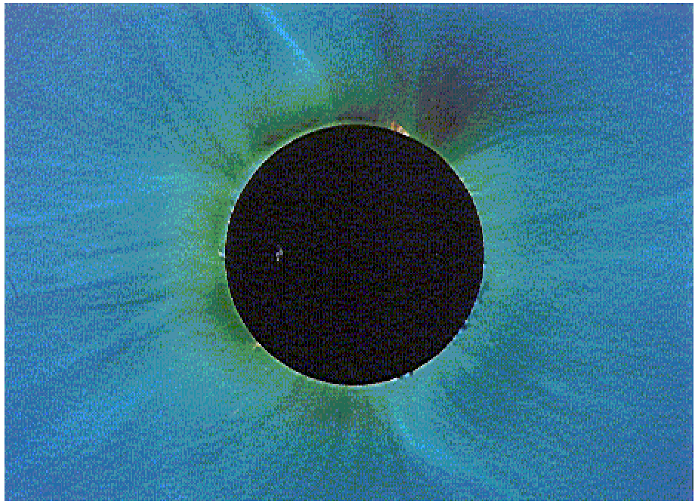
4 H -> He +heat + 2e + 2 ν_e

- This is simply a consequence of the conservation of electric charge and (family) lepton number



- Neutrinos , which are the most penetrating radiation , manage to cross the star (Pontecorvo '46) ; **we must reveal them in order to have the proof of the sun's energy source**

Underground physics

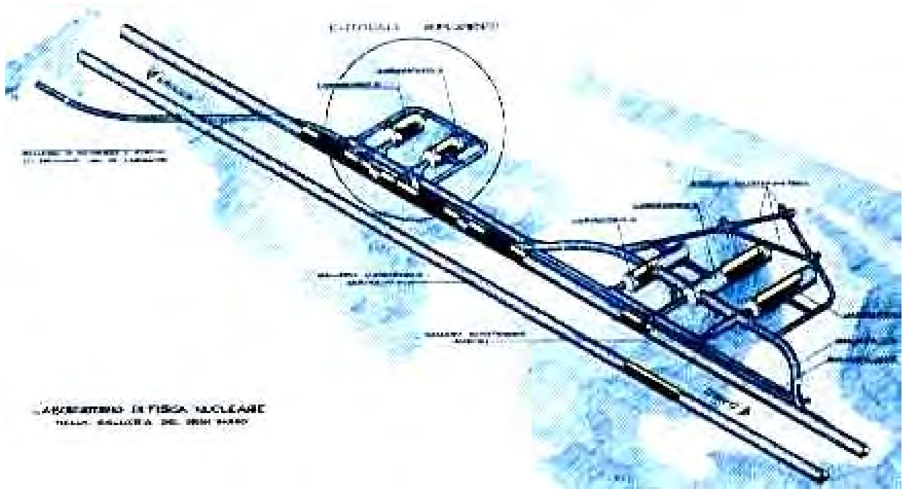


To reveal an elusive, penetrating, radiation we must shield the detector from any other radiation

LNGS : Laboratori Nazionale del Gran Sasso

The laboratory of the cosmic silence

The frontier of zero radioactivity



The imprints of nuclear reactions in the sun

- Gallex experiment in the underground laboratories of Gran Sasso detected neutrinos coming from the nuclear fusions inside the sun.

- Gallex has demonstrated that the energy of the sun is produced by nuclear reactions taking place inside it.

Gallium Experiment at Gran Sasso

GALLEX

INTERNATIONAL
SOLAR NEUTRINO RESEARCH
COLLABORATION

Seen and unseen things

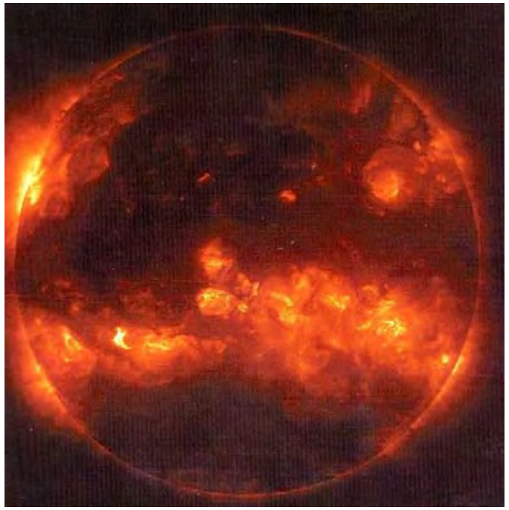
•The signal which was observed by Gallex was about ½ than that expected from energy conservation

•A) May be than in the sun take place only half of the expected fusion reactions ?

•B) Half of electron neutrinos have turned into other types of neutrinos ?

- **Experiments on neutrino oscillations have told us that B is the right answer**
- **In other words , the telescope with neutrinos has been calibrated !!!**

What else can be seen with neutrinos ?

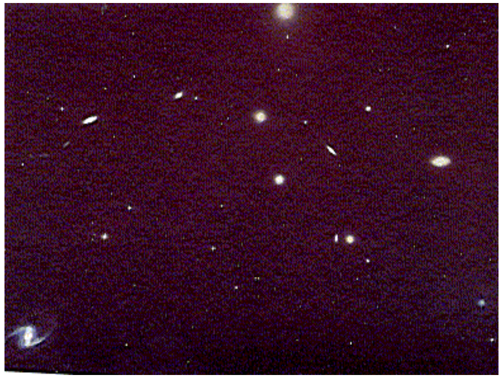


The Interior of the Sun

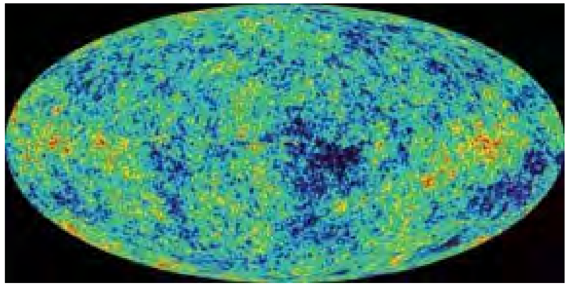
The interior of the Earth

The interior of supernovae

Neutrinos form the Galaxy



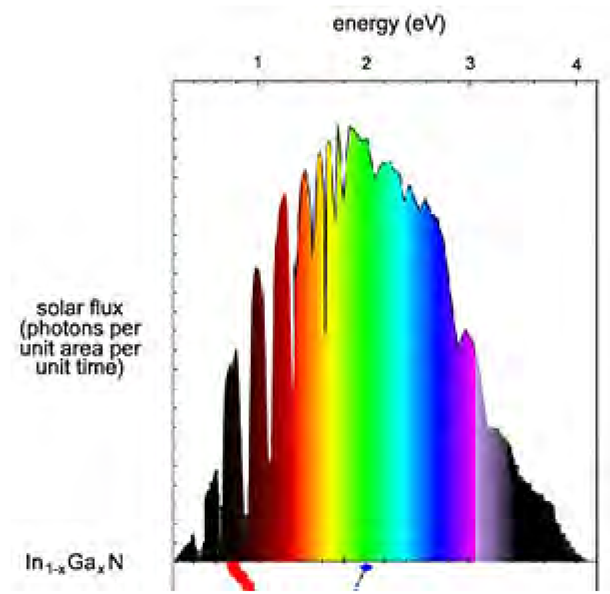
Dark matter in the universe

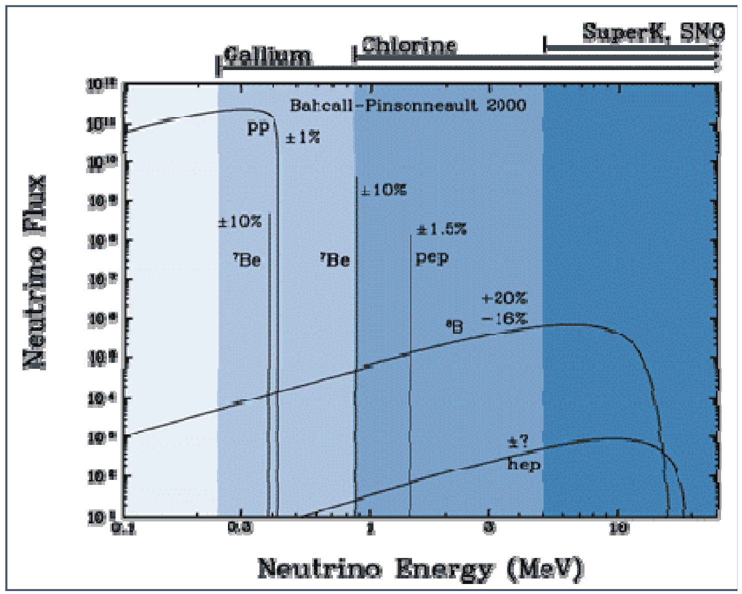


The Big Bang

The solar interior, seen with neutrinos

- Now that we understand neutrinos , we can use them to study the Sun .
- A neutrino spectroscopy of the Sun is in progress , by measuring the neutrino radiation at different energies
- This comes from the Sun's core, otherwise inaccessible.
- At LNGSG the most difficult neutrinos , have been detected, those with low and medium energy
- In the future also CNO neutrino will be studied…

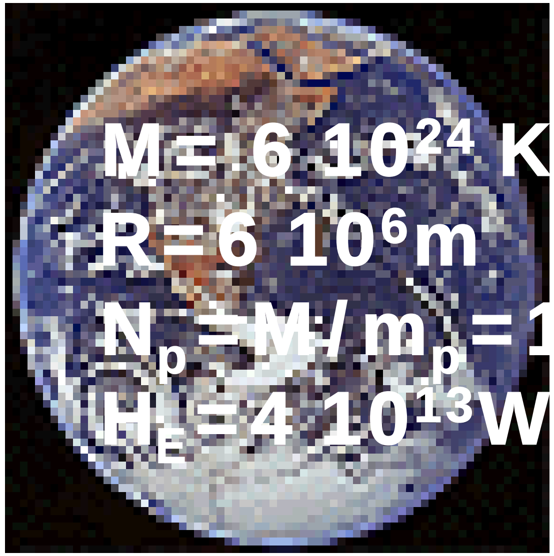




Geoneutrinos: (anti) neutrinos from the Earth

- Earth is radioactive
- What is the content of radioactive elements inside Earth?
- Detection of antineutrinos produced in the Earth interior form U, Th and K-40 decay chains is the method to study Earth radioactivity and to measure the radiogenic contribution to terrestrial heat flow.

The Earth energy inventory



It is not at all easy to understand the dominant contribution to the Earth energy production.

• The present heat flow H_E=40 TW can be sustained by an energy source U for a time $t=U/H_E$:

•a)"chemistry"*): $U \approx (0.1 \text{ eV}) N_p = 6\ 10^{31}$J ->$t_{ch}=5\ 10^{10}$ y

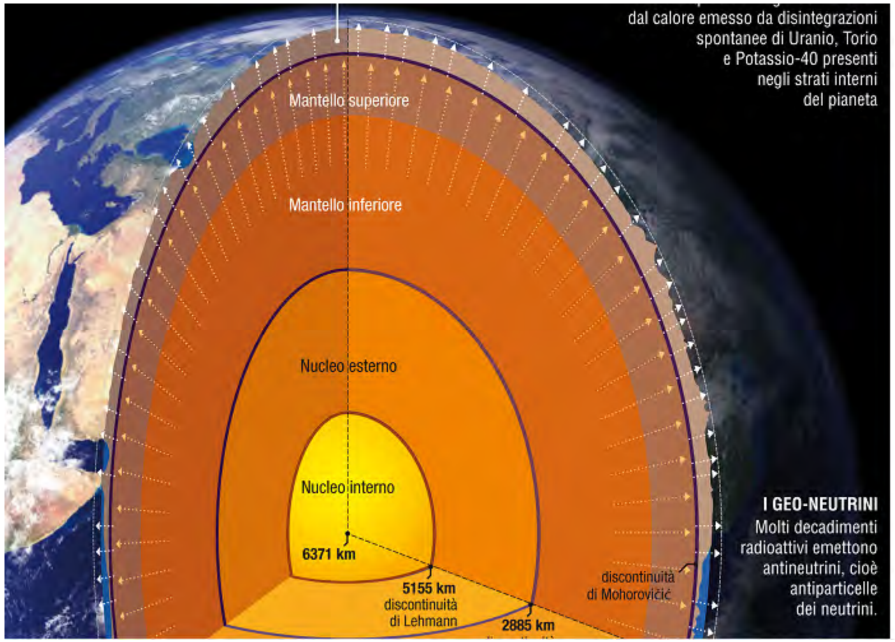
•b) gravitation $U \approx GM^2/R = 4\ 10^{32}$J ->$t_{gr}=3\ 10^{11}$y

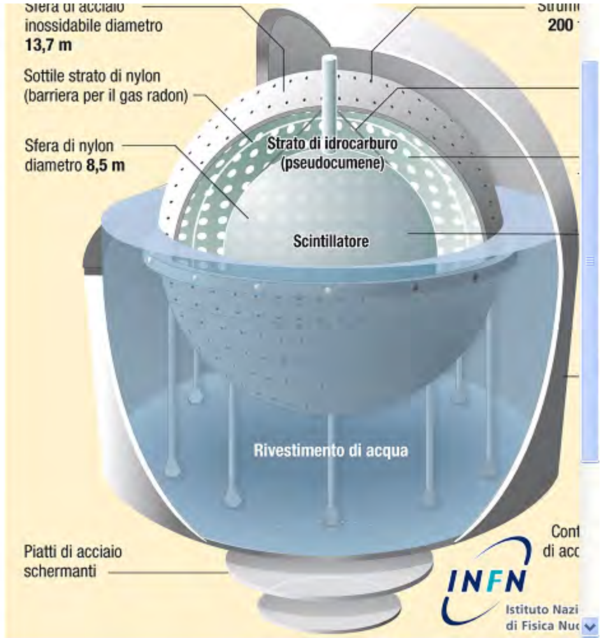
•c) nuclear **) $U \approx (1\text{MeV}) N_{p,rad} = 6\ 10^{30}$J -> $t_{gr}=5\ 10^9$ y

• **Thus all energy sources seem capable to sustain H_E on geological times.**

*)actually it means the solidification (latent) heat, see later
**)the amount of radioactive material is taken as M_{rad} » 10^{-8} M_{Earth}

BOREXINO at LNGS has opened a window on the insterior of the Earth





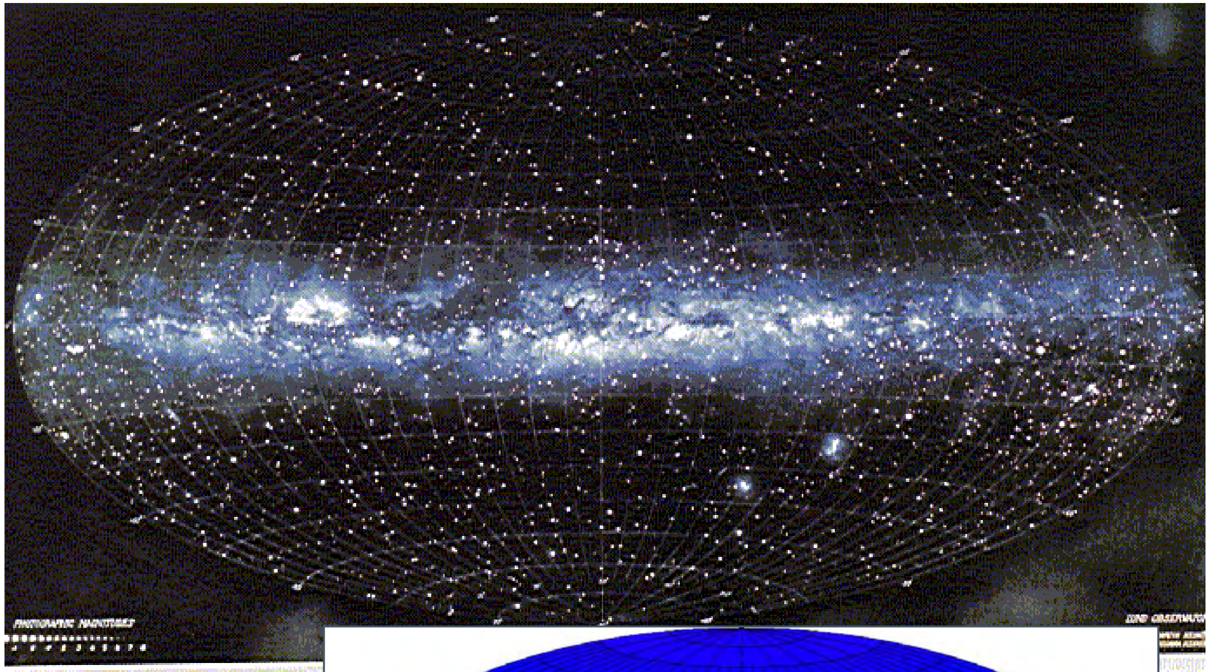
More data from Kamland in Japan and in the future from SNO (Canada) and JUNO (China) will confirm / disprove current theories about the origin and composition of the earth

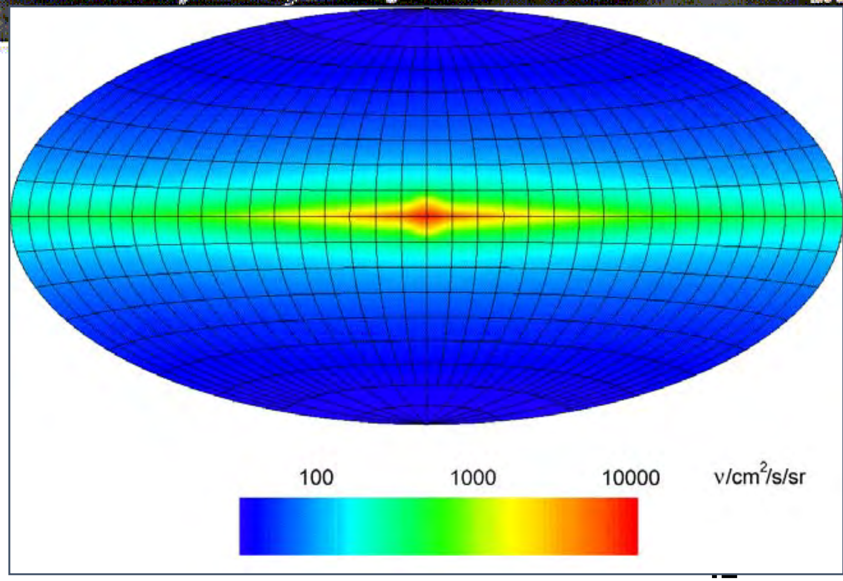
Neutrinos from Supernovae

- Just 0.1 % of the energy of a supernova ' in visible radiation , and 99.9 % are carried by neutrinos.
- In 1987 , for the first time SN neutrinos have been revealed
- Neutrinos from SN are and will be the primary instrument for the study of the internal structure.

Neutrinos from the Galaxy

- In our Galaxy some 10^{11} Stars are shining
- Each of them is producing neutrinos
- How will theGalaxy look in a neutrino telescope?





Dark Matter in the Universe

- Within the galaxies and between galaxies there is matter that does not shine, It is dark .
- Dark matter makes up 90 % of the Universe , but we do not know what is made of
- We know that neutrinos have mass , and thus contribute to the dark matter .

What is the contribution of neutrinos to the missing mass?

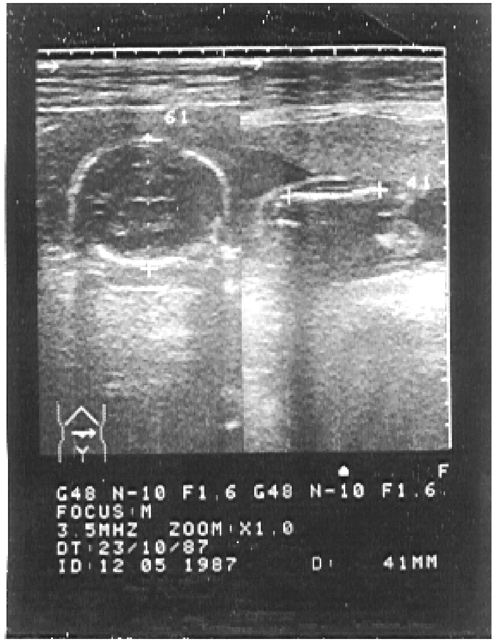
What is the mass scale of neutrinos ?

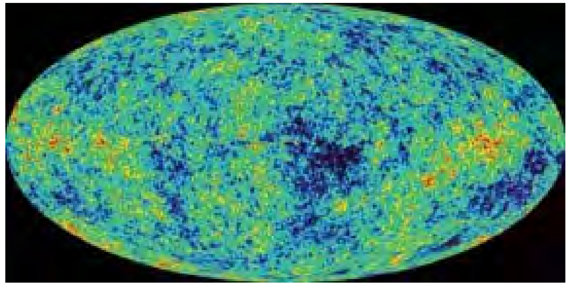
- Today we know that neutrinos have different masses , we measure the differences but we do not know the scale

- There are various experiments in progress and planned , but for now we only have an upper limit on the scale

Neutrinos from Big Bang

- Look far in space means look back in time .
- Today we see the traces of the Big Bang, the background radiation (e.m) that permeates the universe .
- This photographs the universe 300,000 years after the big bang .
- We have no antecedents pictures, because the universe was too dense and light could not escape
- There is another background radiation , the neutrino , who manage to escape 1s after the Big Bang .
- **Reveal it, is the great dream of all neutrinists!!**



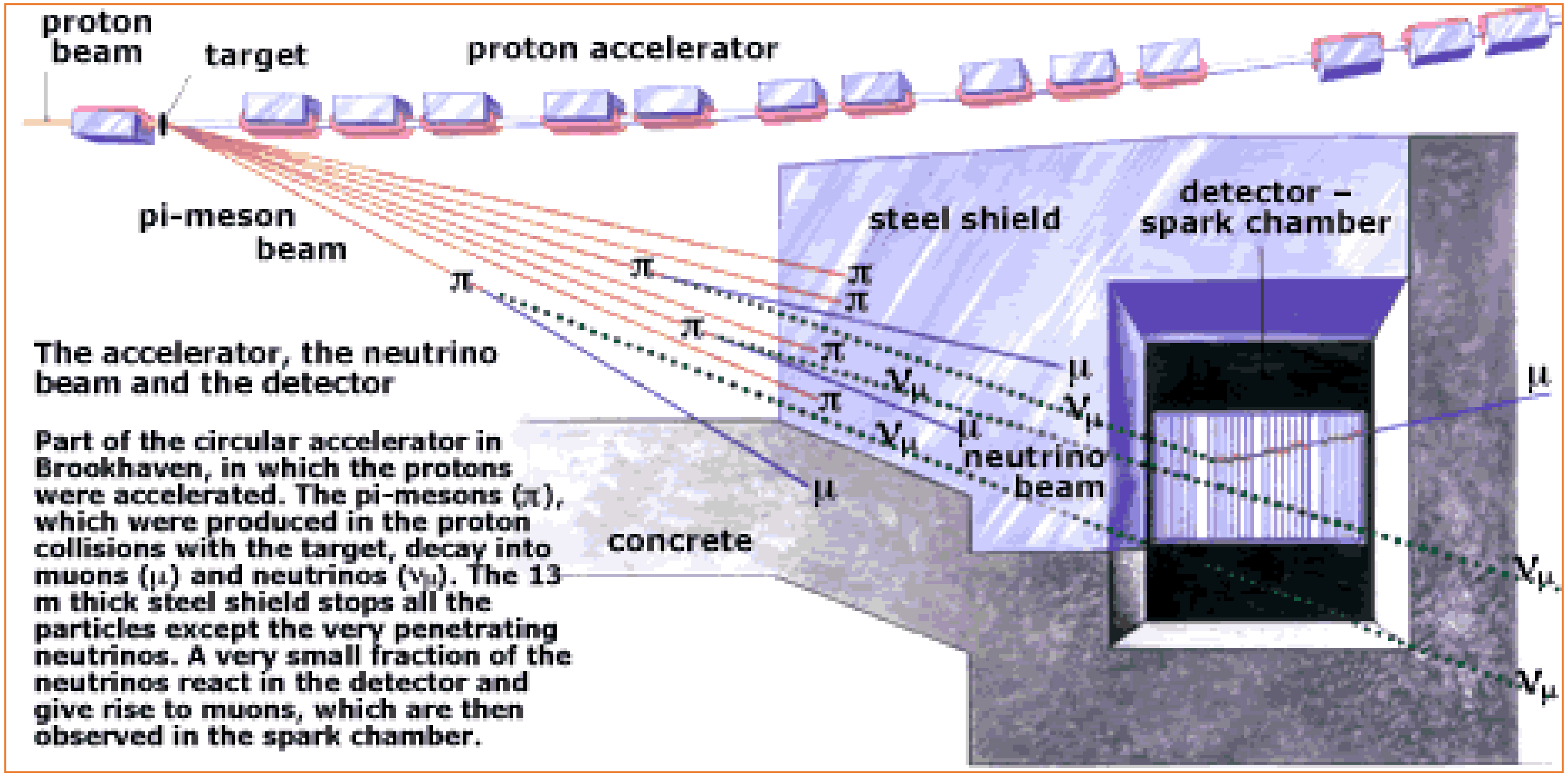


Grazie

Additional Readings, questions and problems

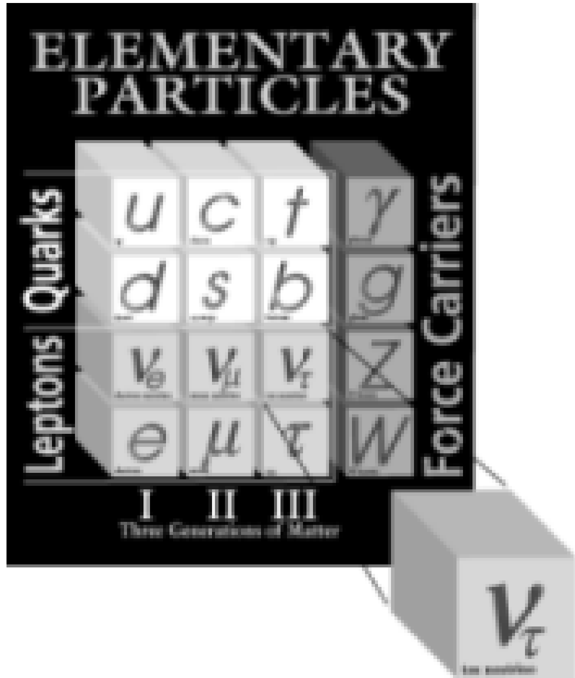
Two neutrino experiment

- The π^+ meson decays mainly in $\pi^+ \rightarrow \mu^+ + \nu_\mu$ where we have denoted with ν_μ the neutrino produced together with μ^+ .
- This is not the same state that accompanies the e^+, that is ν_e . If so ($\nu_\mu = \nu_e = \nu$) in a subsequent collision with nuclei neutrinos should induce reactions ν+Z $\rightarrow$ Z+1 + e.
- Ledermann, Schwartz and Steinberger observed that the neutrinos associated with μ^+ produce the reaction ν+Z $\rightarrow$ (Z+1) +μ but not ν+Z $\rightarrow$ Z+1 + e.



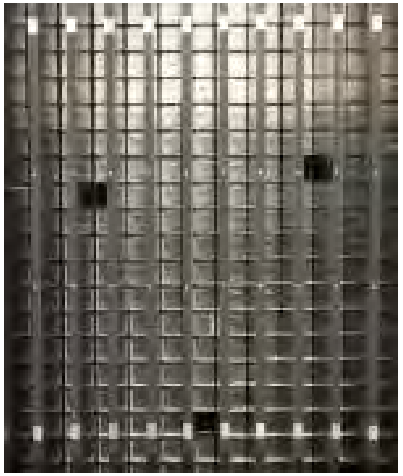
Lepton family numbers

- In 1975 the charged lepton τ was discovered and in 2000 reactions induced by neutrinos ν_τ on nuclei were observed
- The picture that emerges is the conservation of lepton family number, defined for each family $\alpha=\varepsilon,\mu,\tau$ as $L_\alpha=1$ for l^+_α and ν_α, 0 for the other families, the opposite for antiparticles.
- Clearly $L= L_e+L_\mu+L_\tau$.
- The conservation of the family numbers imply the conservation of lepton number, but the converse is not true: the lepton number can be conserved but the family numbers may be violated.



Opera al Gran Sasso

- •OPERA =Oscillation Project with Emulsion-tRacking Apparatus).
- •Neutrinos "shot" from the European laboratory of CERN in beams directed to the Gran Sasso: in a mere 2.4 milliseconds they travel 732 kilometres beneath the Earth's crust to the core of the Gran Sasso Mountain
- •During their journey, there is the possibility that some of them “change” their nature.
- •A few e candidate neutrino that turned (in particle physics is called “oscillation”) from a muon neutrino into a tau neutrino has been detected by the OPERA scientists since 2010.



L'esperimento CNGS (Cern Neutrinos to Gran Sasso)

Obiettivo

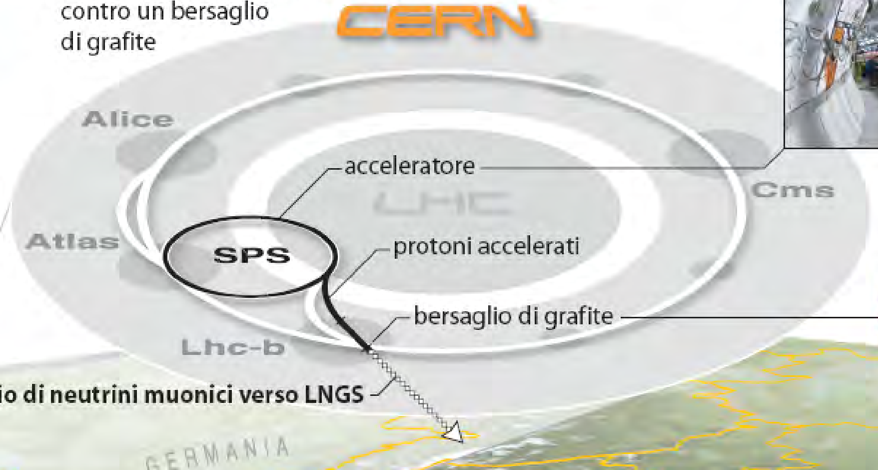
Osservare per la prima volta in modo diretto l'**oscillazione del neutrino.**

$\nu_\mu \rightarrow \nu_\tau$

Questo consentirà anche di ricavare preziose informazioni sulla massa e sulle proprietà fisiche di questa particella

Come funziona

1 Al **CERN** di Ginevra, un fascio di neutrini muonici puntato verso i Laboratori Nazionali del Gran Sasso (LNGS) dell'Istituto Nazionale di Fisica Nucleare (INFN) viene prodotto facendo scontrare dei protoni accelerati contro un bersaglio di grafite



2 I neutrini attraversano la crosta terrestre per **732 km** e, viaggiando quasi alla **velocità della luce** giungono a destinazione dopo **2,4 millisecondi**

INFN Istituto Nazionale di Fisica Nucleare

OPERA

3 Ad attenderli ai **LNGS** c'è **OPERA** che fotografa i prodotti della loro interazione con i nuclei del piombo di cui è composto il rivelatore.

OPERA volume totale: **2.000 m³**
peso totale: **4.000 tonnellate**
(come 7 Airbus A380)

Il rivelatore principale è costituito da **150.000 mattoncini.**
Ogni mattoncino

The Earth energy inventory: gravitation ...and the rest

•Gravitational energy form building the Earth should have been radiated away very early ($t= U / pR^2sT^4 \sim 10^6$ y).

•Similarly, “solidification”have produced heat mai

and most heat should have been radiated away.

•Gravitation and solidification, however, can work still today:

-There is a large fraction of the nucleus which is still liquid (as implied by the fact that only longitudinal waves penetrate into it).It may be that in this region solidification occurs even now.

-With solidification of the core, one forms a higher density material, which sinks to the bottom, releasing gravitaional energy

•All This may contribute an amount L_{LH} »10^{12}W

•Tidal deceleration of the Earth results in dissipation of rotational kinetic energy (E_{rot} » 2 10^{29} J) of similar order of magnitude.

Borexino:expectations and results on geo-neutrinos

•Predict a total of 20.7 events in 24 months

(G=6.3 R=14.Bk=0.4)

•The HER can be used to test the experiment sensitivity to reactors

•In the LER one expects comparable number of geo-nu and reactor-nu

•Observe 21 events in 24 months, attributed to

R=10.7 $_{-3.4}^{+4.3}$

G= 9.9 $_{-3.4}^{+4.1}$

BK=0.4

•One event per month experiment !