Neutrino Oscillations

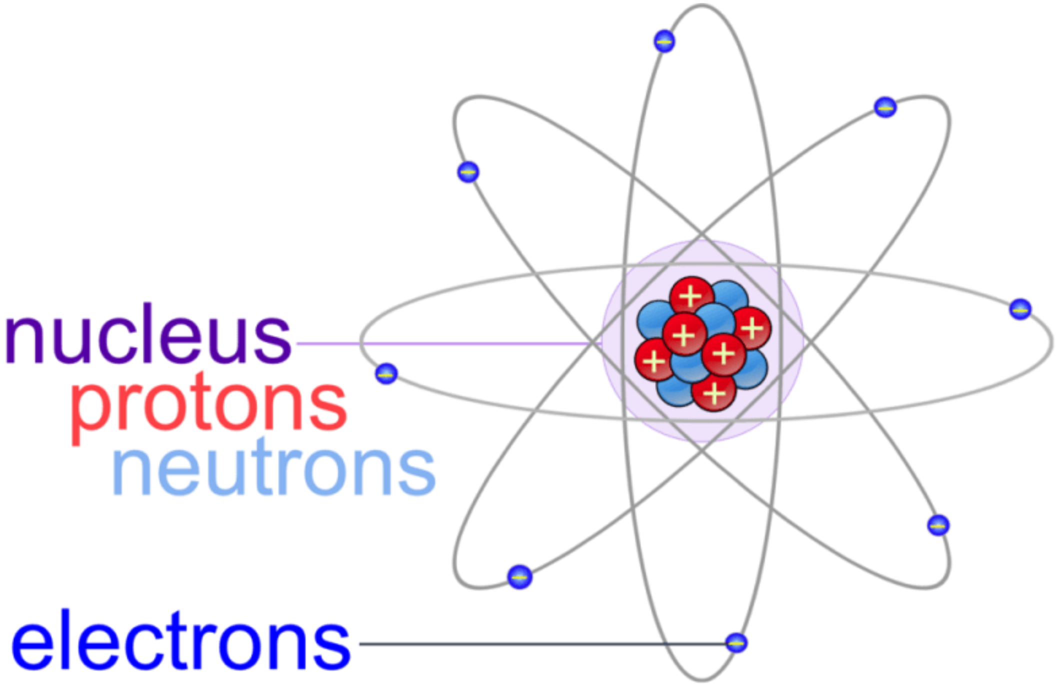
Stefan Söldner-Rembold
University of Manchester

Academic Training Lecture Programme
May 2021

Lecture 1

Neutrino Oscillations and the PMNS Matrix

What are we made of?



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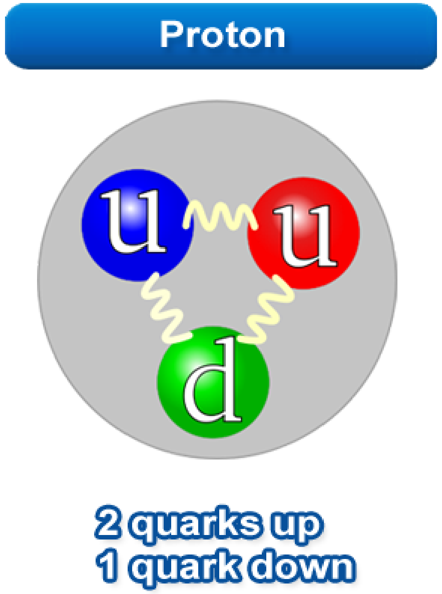
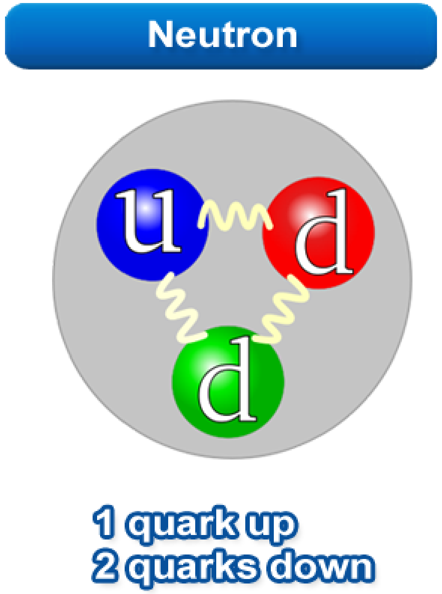
What are we made of?

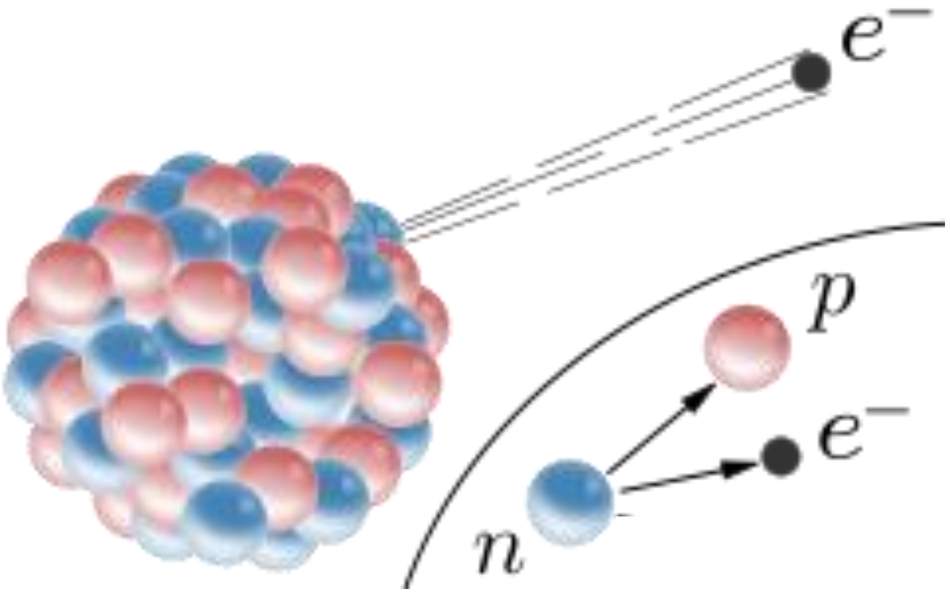




Beta Decay

Neutrons are not stable

"neutron→ proton + electron"



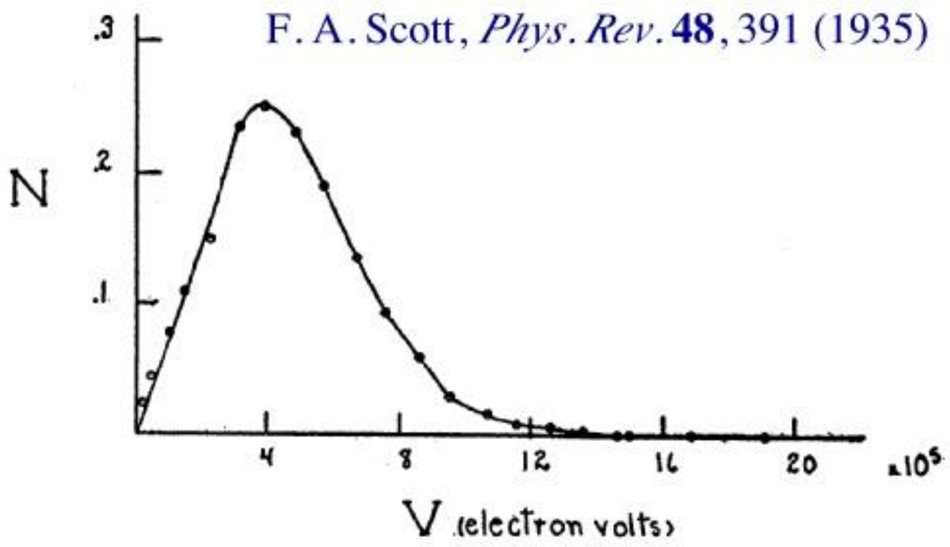


FIG. 5. Energy distribution curve of the beta-rays.

Liebe Radioactive Damen und Herren,

Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

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. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben 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.

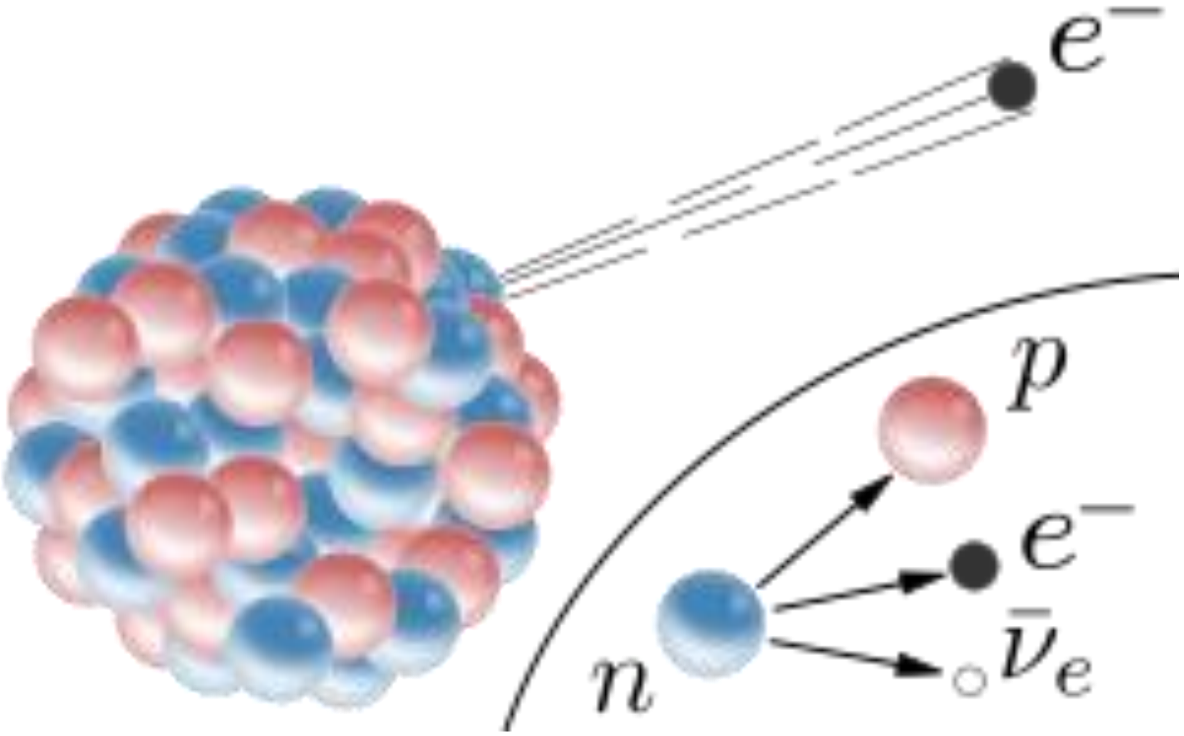
Dear Radioactive Ladies and Gentlemen,

…I have hit upon a desperate remedy…

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

--Signed, W. Pauli

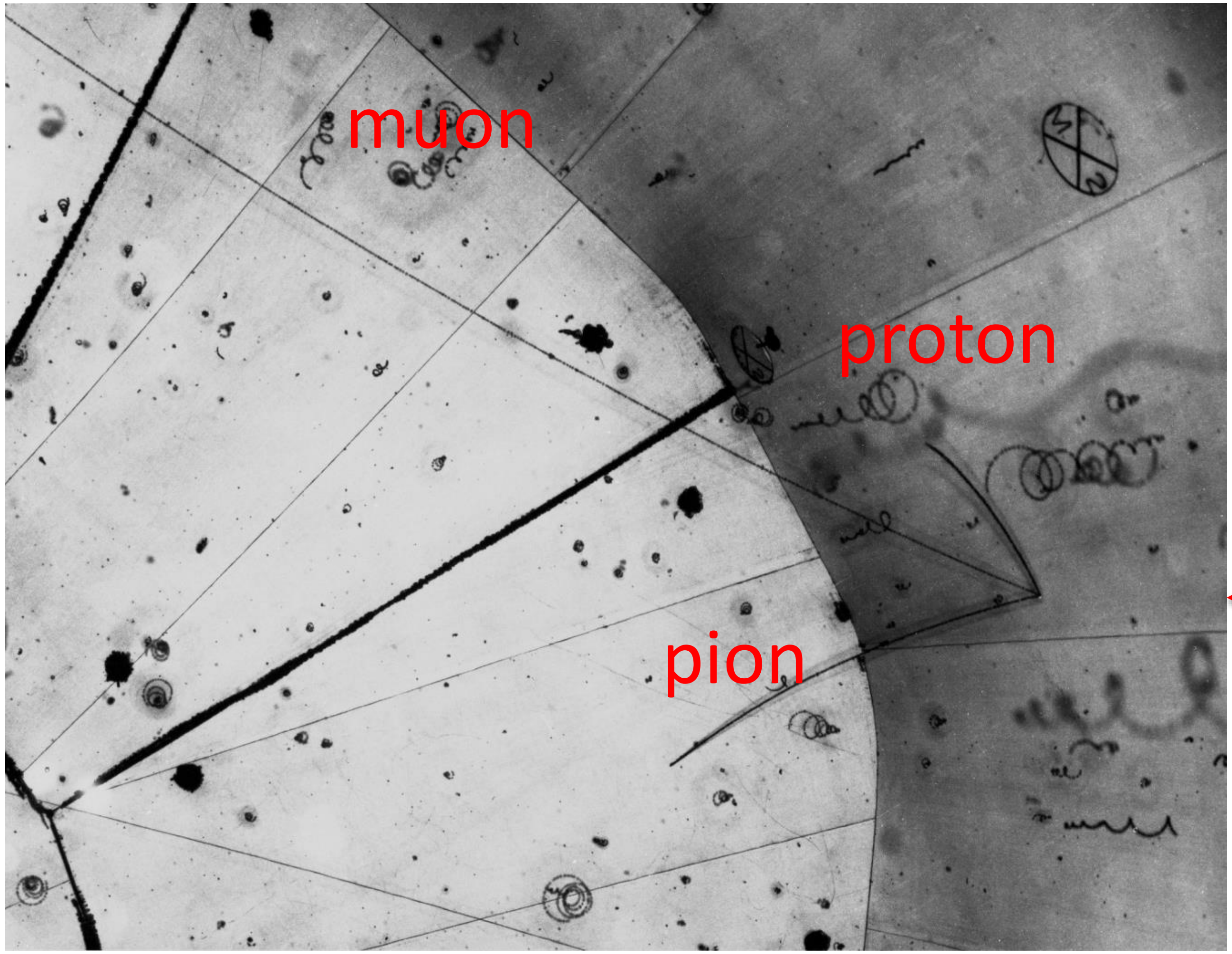
Dear Radioactive Ladies and Gentlemen,



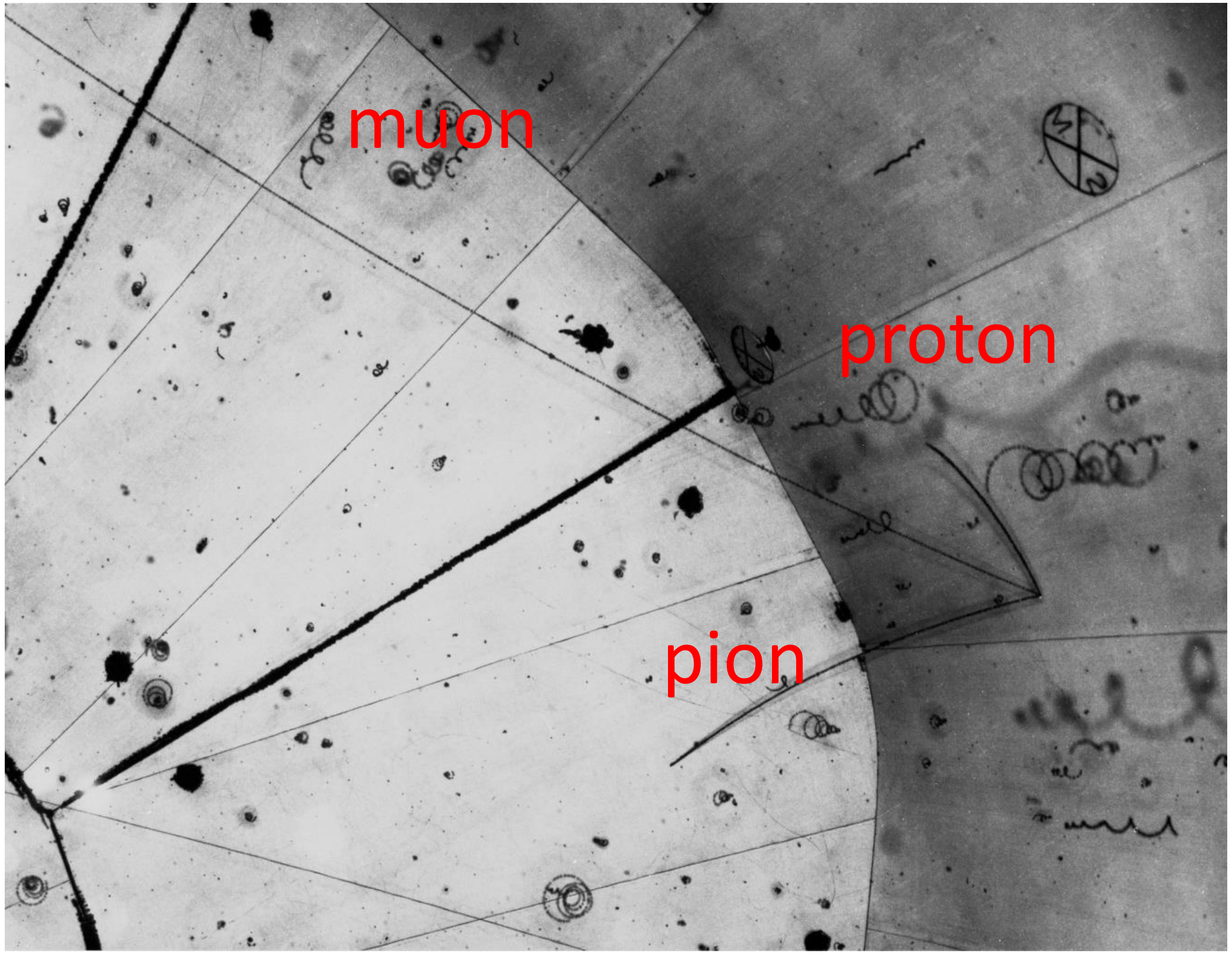
- Enrico Fermi (re-)named the new particle ‘neutrino’.
- Discovered in β decays from reactors in 1956:

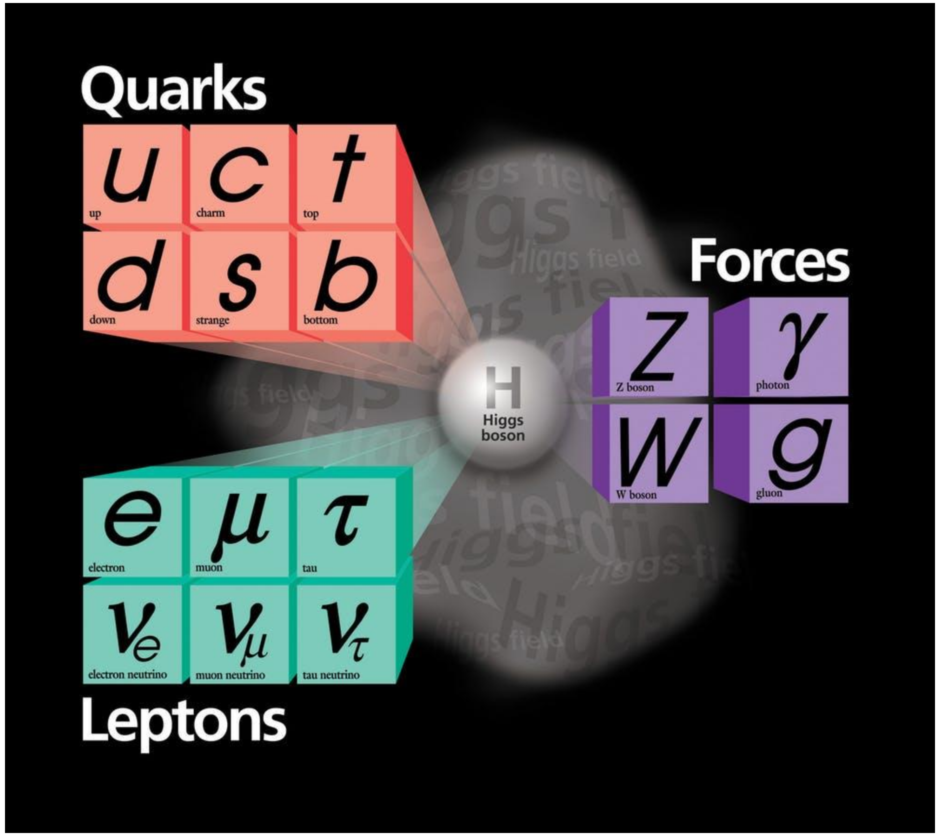
$$\bar{\nu}_e + p \to n + e^+$$

Hydrogen Bubble chamber, Argonne, 1970



(muon)-neutrino

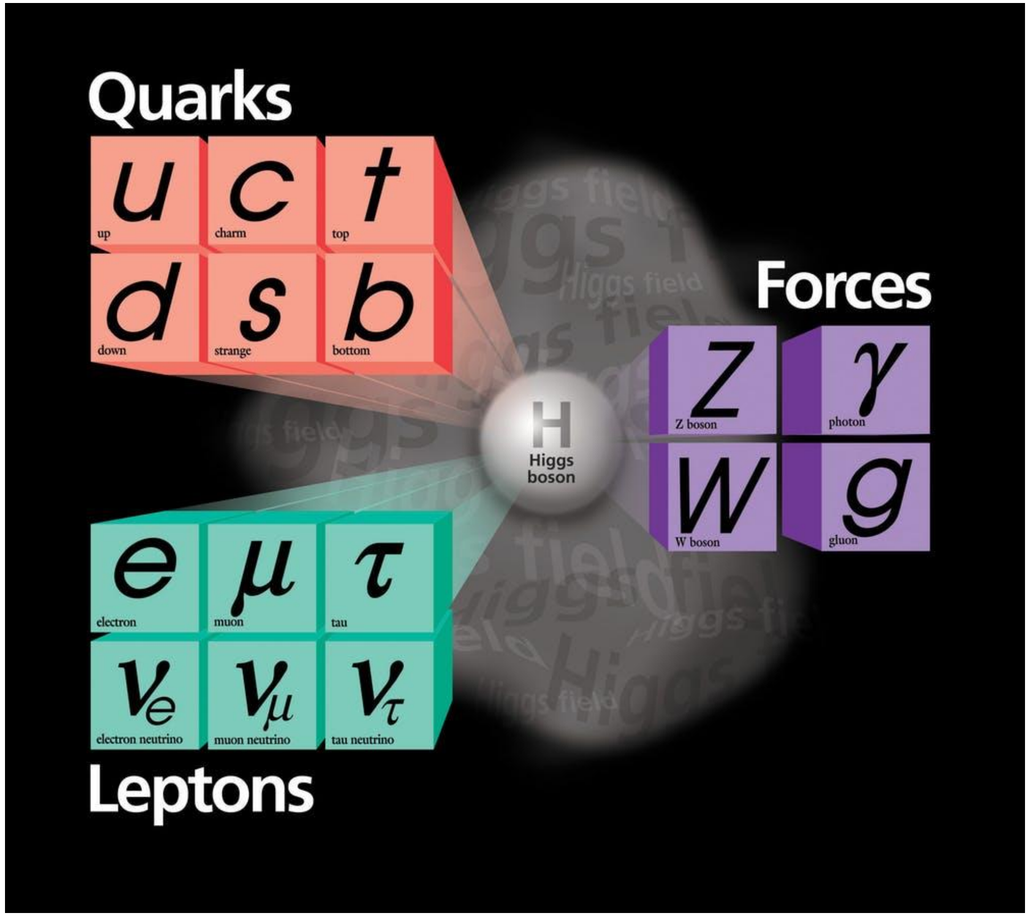




- Charged and neutral leptons come in pairs
- ”Flavour” of outgoing charged lepton defines neutrino flavour
- Neutrinos have three flavours (e, μ, τ)

The “Standard Model”

3 families



- Neutrinos are electrically neutral
- Four forces:
  - Strong force (gluon g)
  - Weak force (W and Z boson)
  - Electromagnetic force (photon γ)
  - Gravity (graviton)
- Neutrinos only feel the weak force (and gravity)
- Even though neutrinos appear ”ghost” like and ephemeral, they play an important role in the Universe.

Neutrinos are the most abundant matter particle:
for every proton/neutron/electron the Universe
contains a billion neutrinos from the Big Bang

10^{38} neutrinos per second are produced by fusion processes in the Sun

(with a flux of $\sim 10^{11}/cm^2/sec$ at the Earth)

Neutrinos in a box

In a box of 1 cubic meter, somewhere in the Universe, we have on average

- 10 protons
- 300 million neutrinos

left over from the Big Bang.

Neutrinos are the most abundant *matter* particles in the Universe

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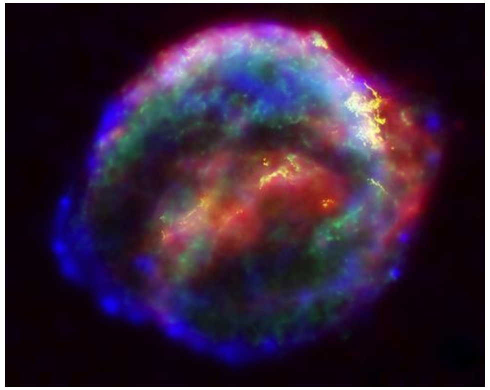
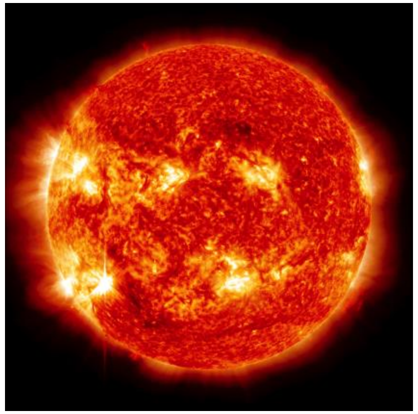
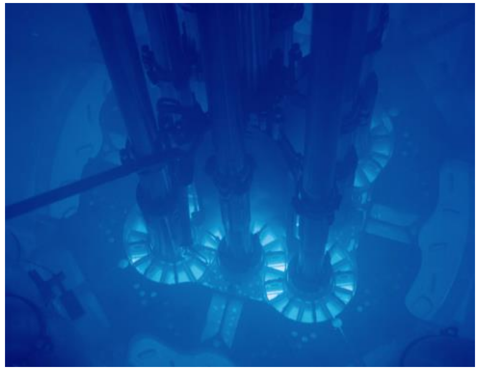
Neutrino Sources (nuclear processes)



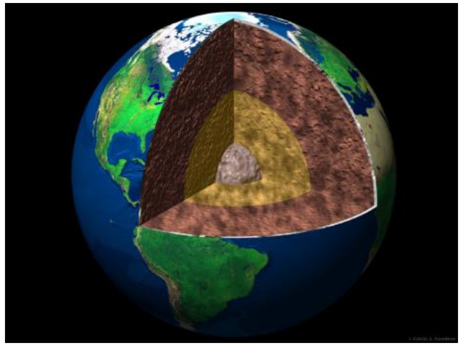
$$p + e^- \rightarrow n + \nu_e$$
$$n \rightarrow p + e^- + \bar{\nu}_e$$



$$p + p \rightarrow {}^2\mathrm{H} + \mathrm{e}^+ + \nu_\mathrm{e}$$



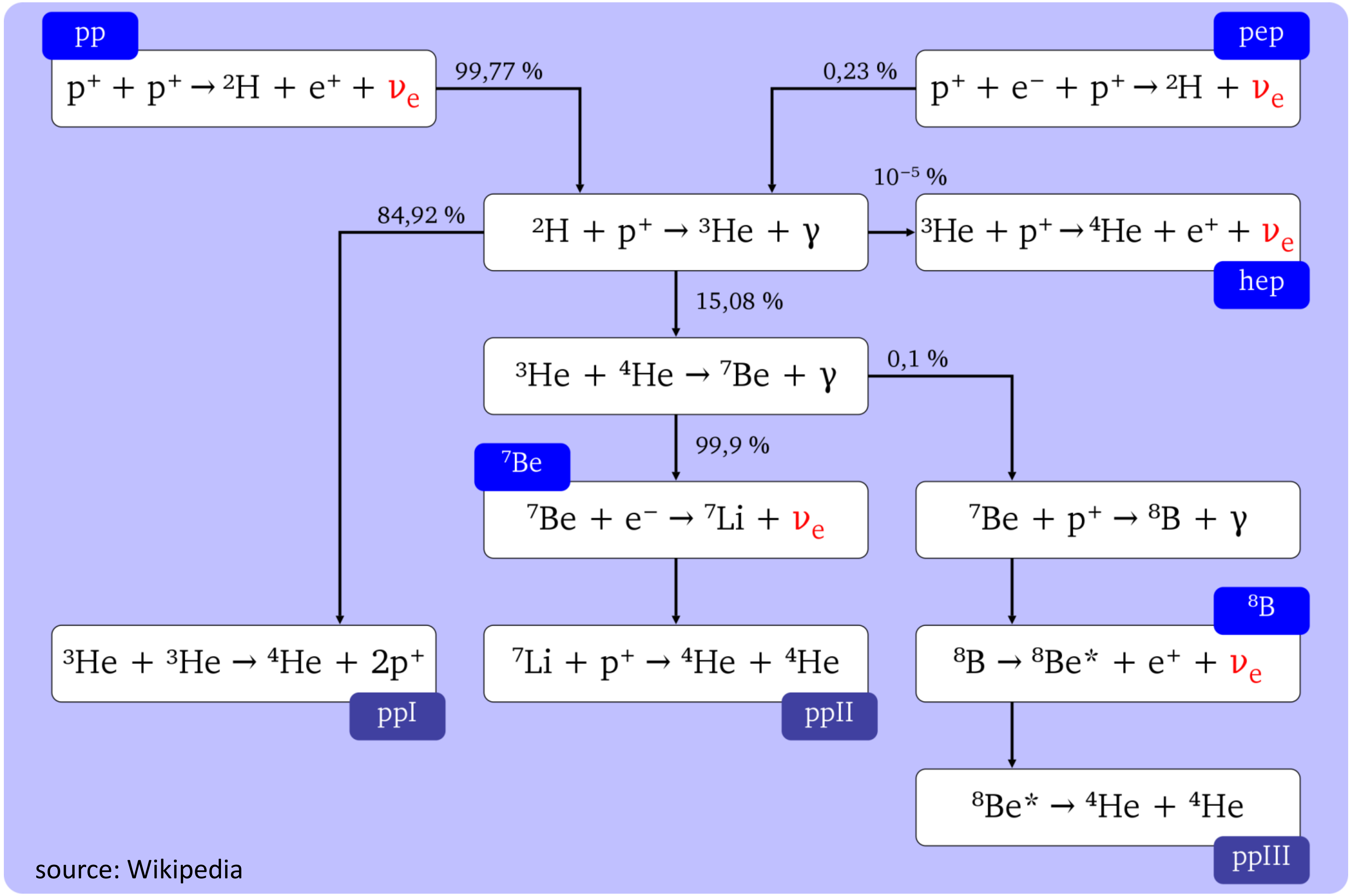
$$n \rightarrow p + e^- + \bar{\nu}_e$$



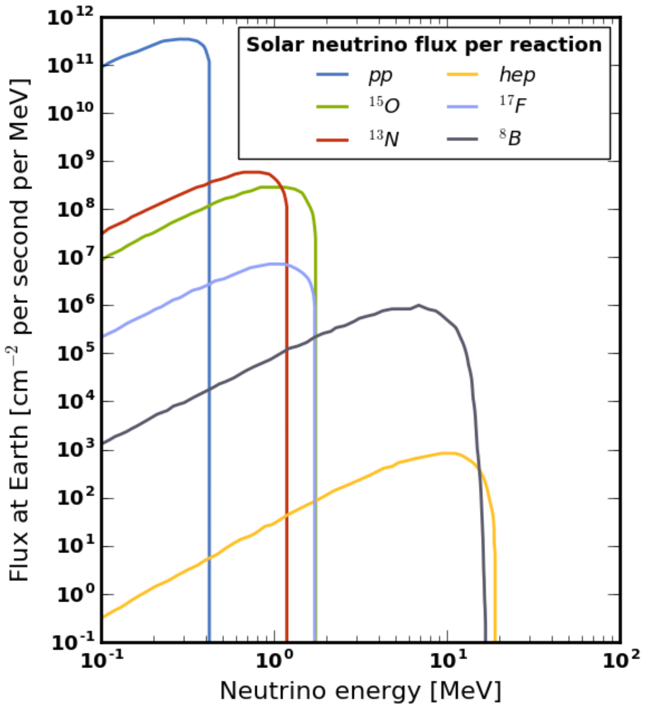
$$\begin{aligned}
{}^{238}_{92}\mathrm{U} &\longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e \\
{}^{235}_{92}\mathrm{U} &\longrightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e \\
{}^{232}_{90}\mathrm{Th} &\longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e
\end{aligned}$$

- Nuclear processes are typically the source of electron-neutrinos.
- Typical energies 1-10 MeV
- Discovery of electron-neutrino by Cowan and Reines at the Savannah River power plant in 1956.

Fusion produces electron-neutrinos in the Sun



source: Wikipedia



Standard Solar Model

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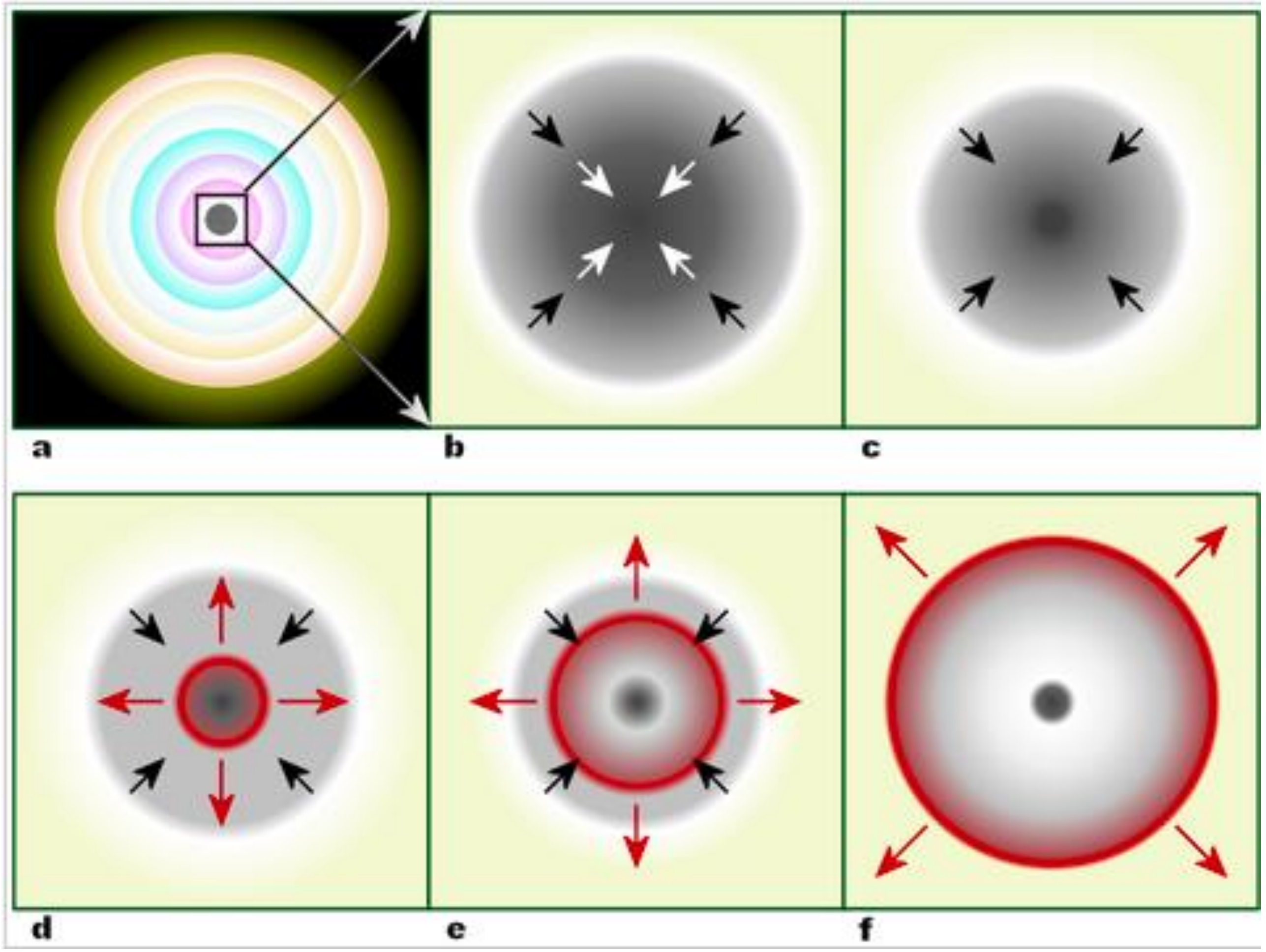
Type II Supernova

Gravitational collapse of a massive start at the end of its life



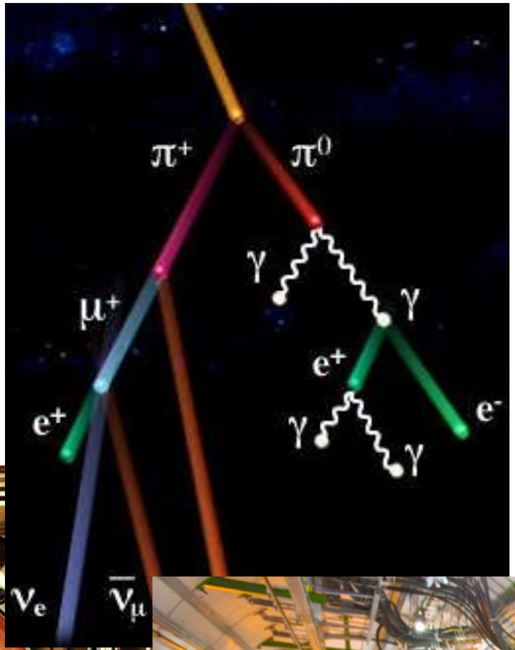
Compact remnant: neutron start or black hole

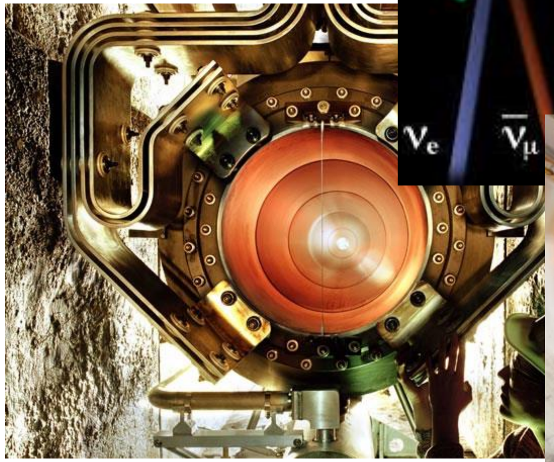
- Dropping an object turns gravitational 'potential energy' into 'kinetic energy' when an object falls.
- As the star falls inward the gravitational energy has to go somewhere:

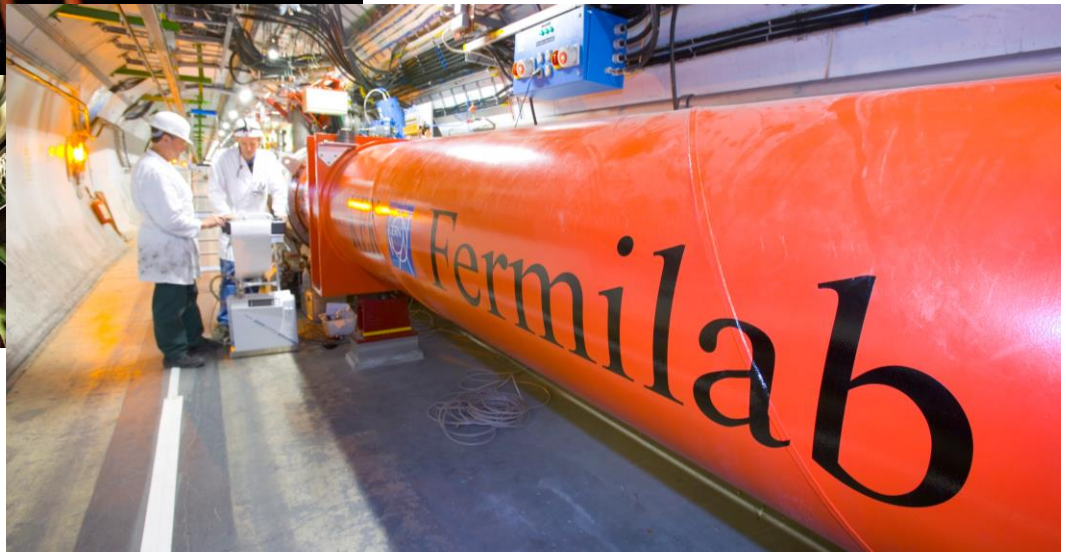
$$p + e^{-} \rightarrow n + \nu_e$$

- Neutrinos only interact weakly, so easiest for them to escape.
- About 99% of the huge binding energy of the neutron star is shed within about 10 seconds in the form of neutrinos.

Neutrino Sources (atmospheric/accelerator)



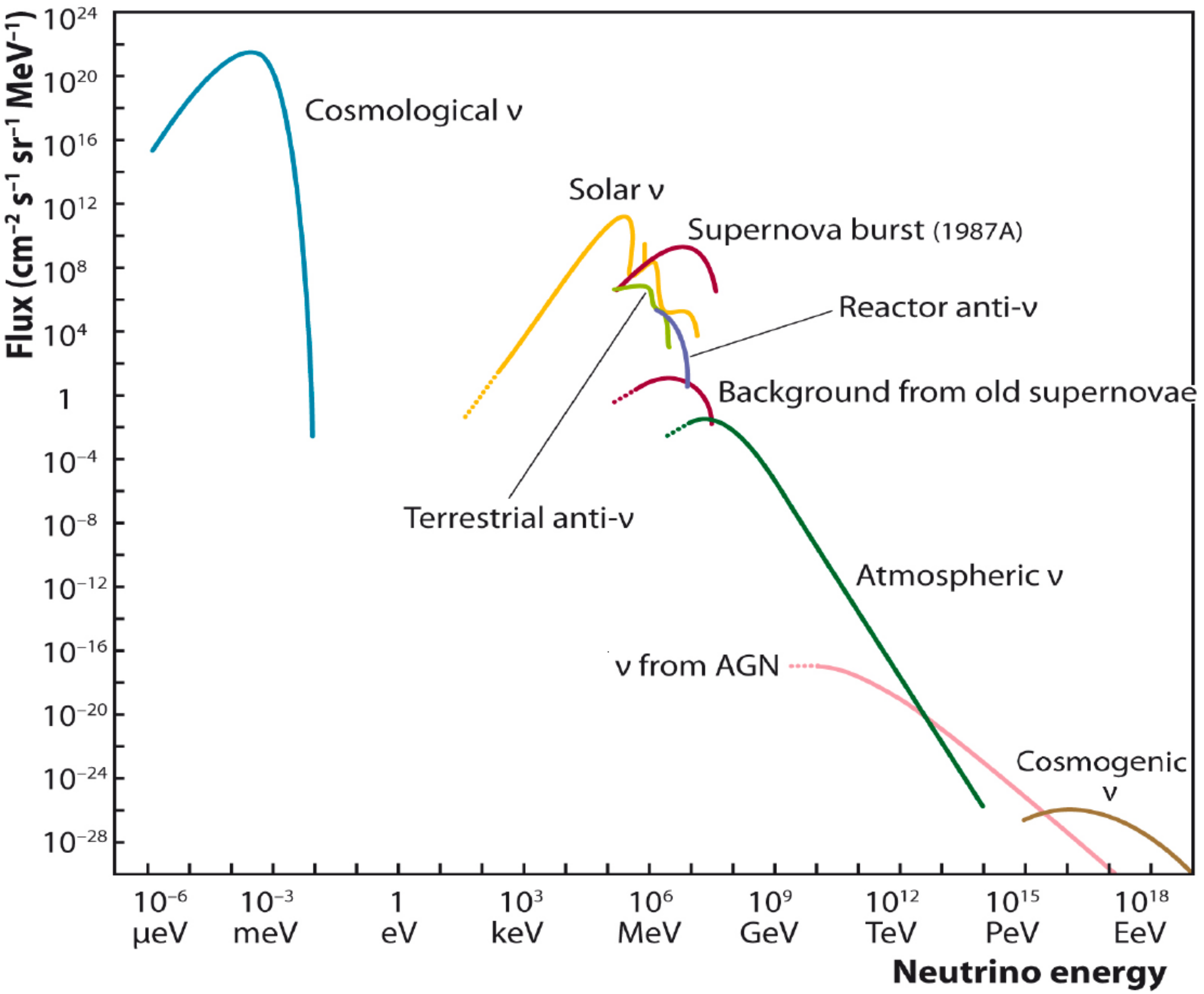




$$p + N \to \pi^{\pm} + X$$
$$\pi^{+} \to \mu^{+} + \nu_{\mu}$$
$$\mu^{+} \to e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

- Pion/kaon production and decay are main source of accelerator and atmospheric neutrinos
- Typical energies ≈ GeV, ratio of ν_{μ}:ν_{e} = 2:1.
- Discovery of muon-neutrino by Ledermann, Schwartz, Steinberger at Brookhaven in 1962.

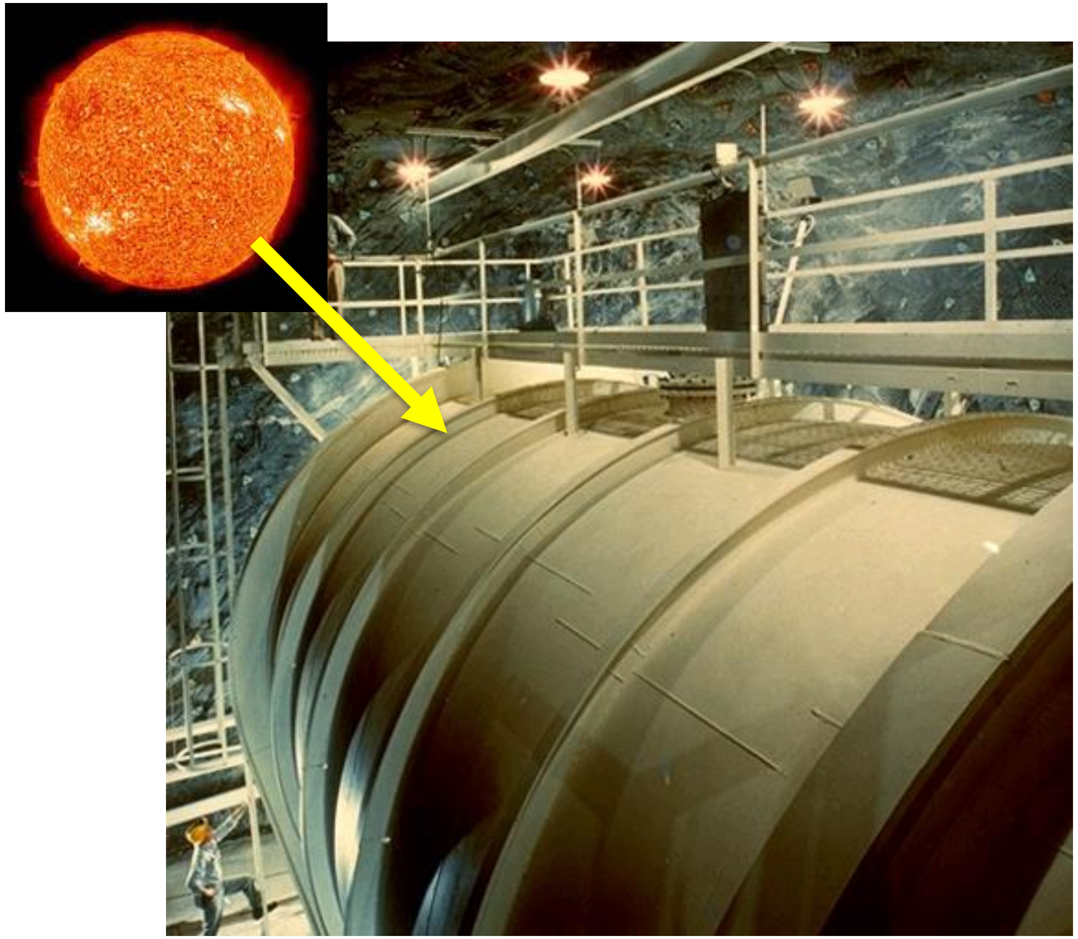
Neutrino sources, flux, and cross section



C. Spiering, arXiv:1207.4952

The missing solar neutrinos

Ray Davis experiment, Homestake Mine, South Dakota

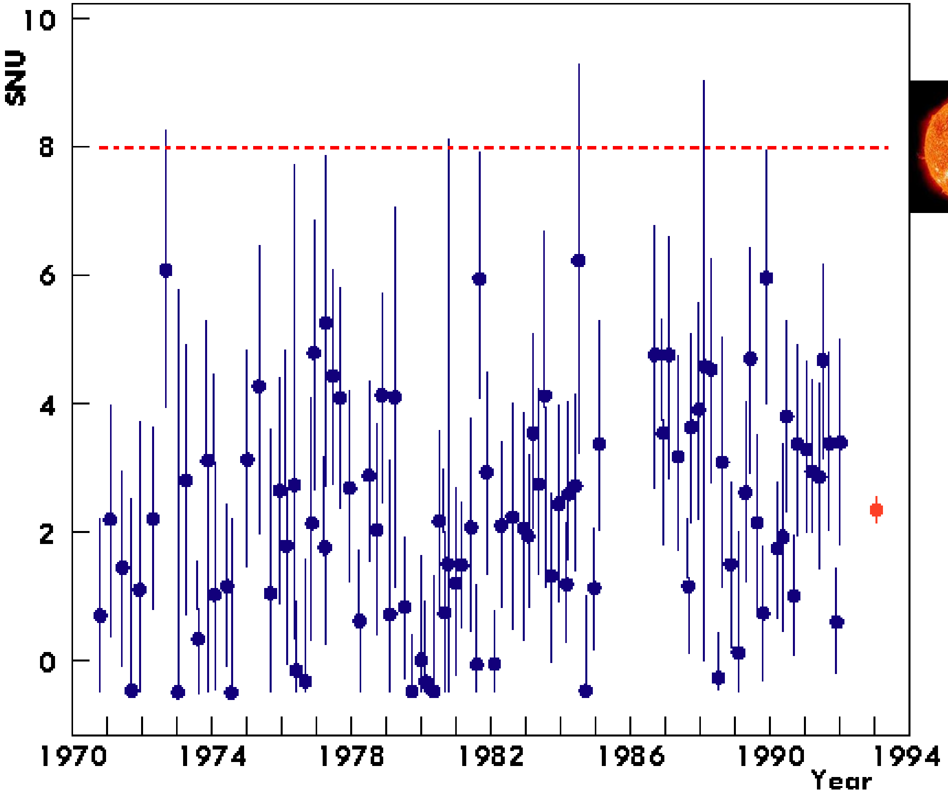


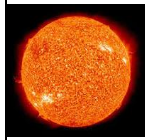
Filled with 390,000 litres of cleaning fluid (C_2Cl_4)

“Inverse β Decay”

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

E_ν > 0.8 MeV





~1/3

Homestake experiment (1970-1994)

- Filter out argon and search for ^{37}Ar decay
- Detecting ~5 atoms of ^{37}Ar per day in 390,000 litres of C_2Cl_4

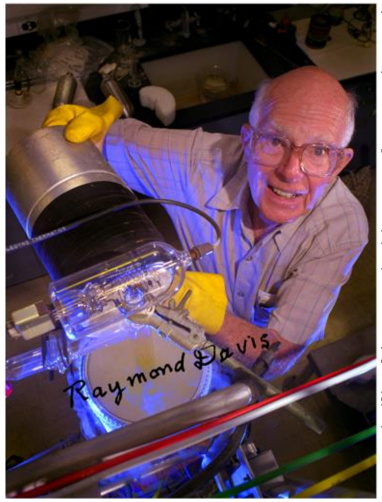
VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

from the bottom of the tank and returned to the tank through a series of 40 eductors arranged along two horizontal header pipes inside the tank. The eductors aspirate the helium from the gas space (2000 liters) above the liquid, and mix it as small bubbles with the liquid in the tank. The pump and eductor system passes helium through the liquid at a total rate of 9000 liters per minute maintaining an effective equilibrium between the argon dissolved in the liquid and the argon in the gas phase.

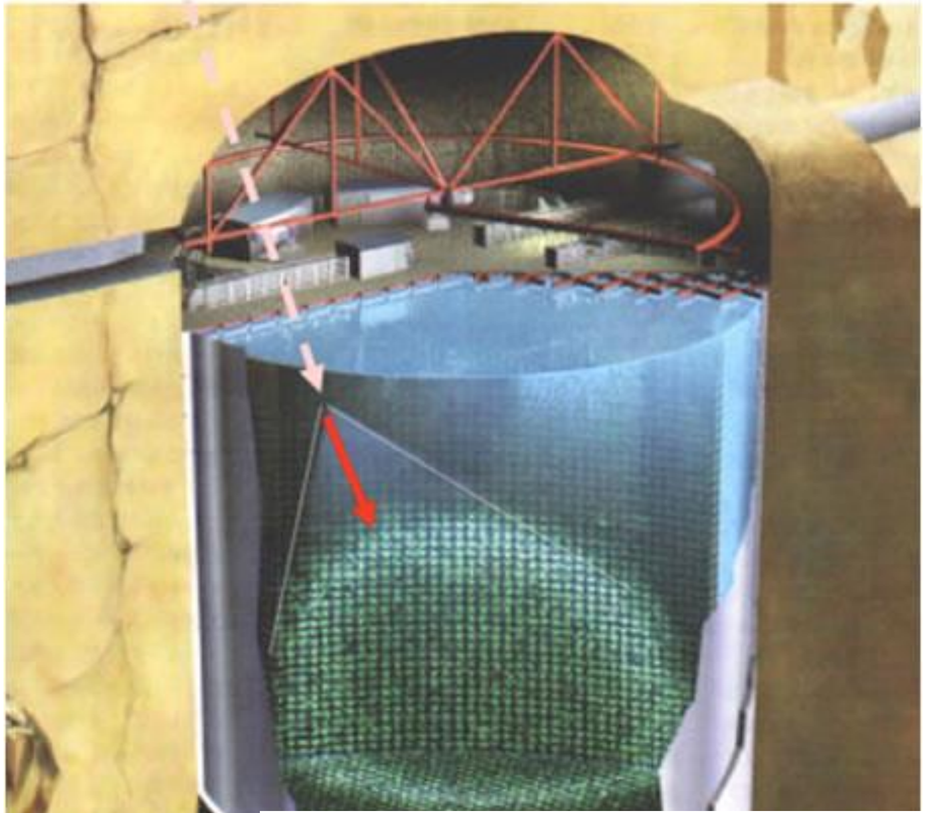
Argon is extracted by circulating the helium from the tank through an argon extraction system. Gas flow is again achieved by a pair of eductors in the tank system, and they maintain a flow rate of 310 liters per minute through the argon extraction system. The tetrachloroethylene vapor is removed by a condenser at −40°C followed by a bed of molecular sieve adsorber at room temperature. The helium then passes through a charcoal bed at 77°K to adsorb the argon

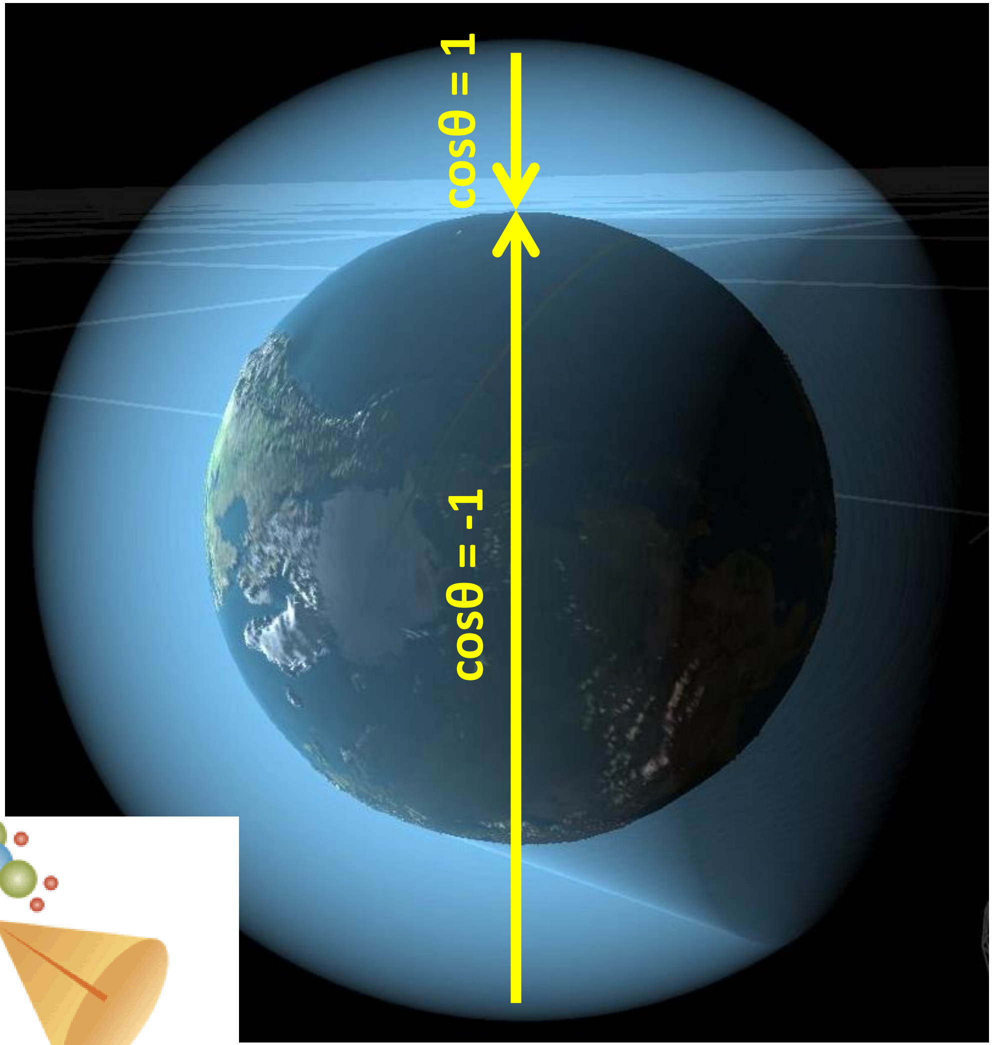
in the mine as indicated in the diagram.

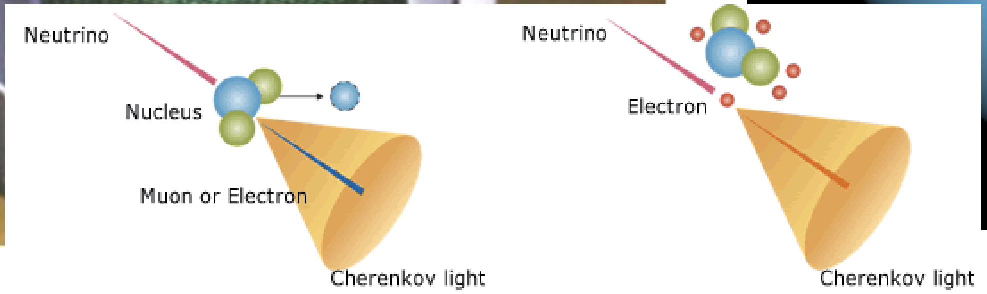
The argon sample adsorbed on the charcoal trap is removed by warming the charcoal while a current of helium is passed through it. The argon and other rare gases from the effluent gas stream are collected on a small liquid-nitrogen-cooled charcoal trap (1 cm diam by 10 cm long). Finally, the gases from this trap are desorbed and heated over titanium metal at 1000°C to remove all traces of chemically reactive gases. The resulting rare gas contains krypton and xenon in addition to argon. These higher rare gases were dissolved from the atomosphere during exposure of the liquid during the various manufacturing, storage, and transfer operations. Krypton and xenon are much more soluble in tetrachloroethylene than argon, and, therefore, they are more slowly removed from the liquid by sweeping with helium. Since the volume of krypton and xenon in an experimental run is comparable with or exceeds the volume of argon, it



Super-Kamiokande

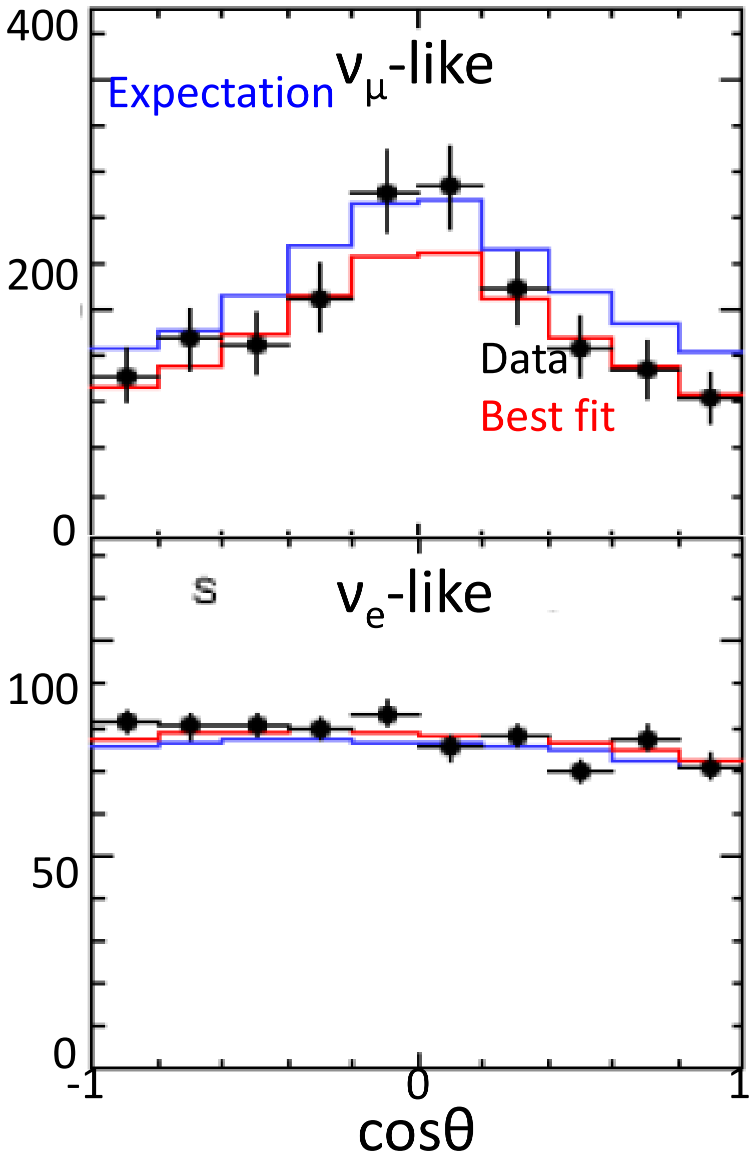


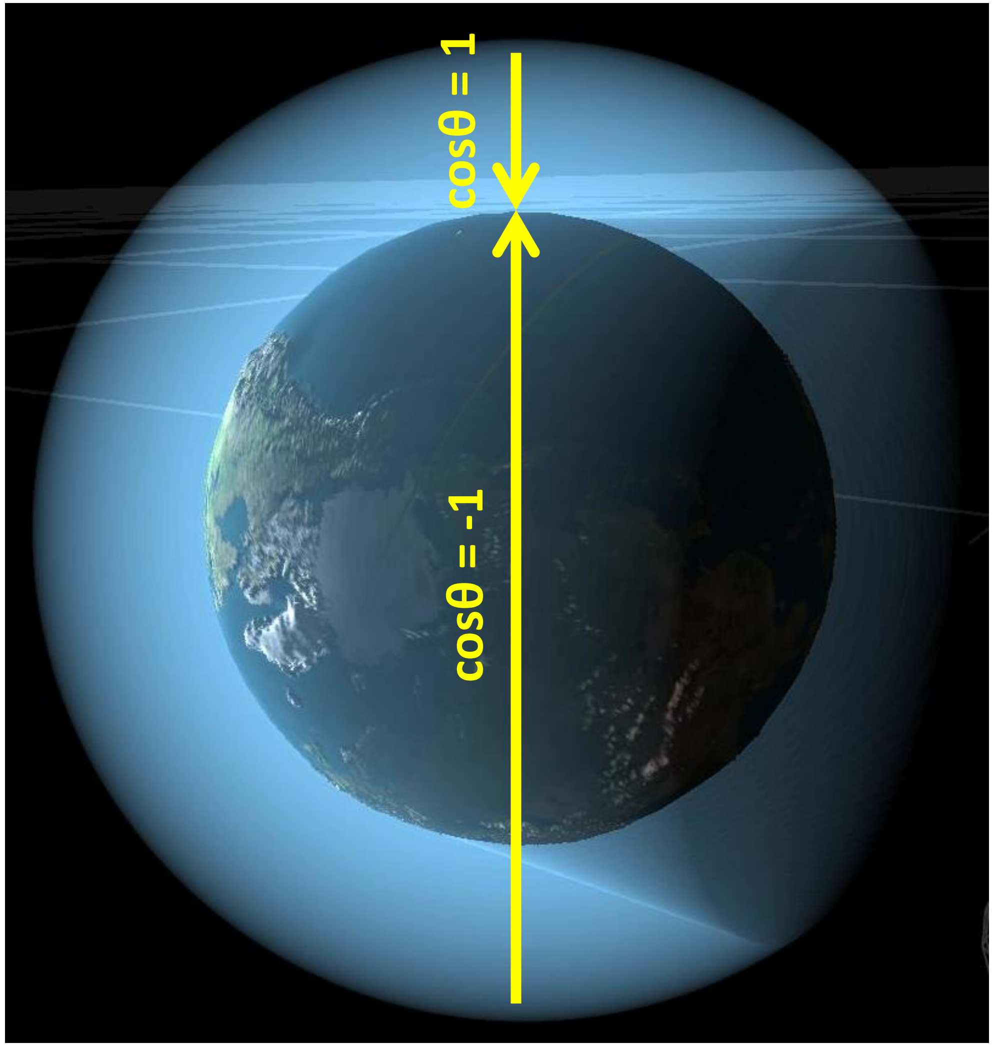




The generated charged particle emits the Cherenkov light.

Super-Kamiokande





What happens to the neutrinos?

- Solar neutrinos
  - Only about 1/3 of expected neutrino flux observed (electron neutrinos)
  - Depends on uncertainties of modelling of the Sun, detector effects?
- Atmospheric neutrinos
  - Muon neutrino disappearance increases with distance traveled
  - Direct evidence for neutrino disappearance
- What happens to the neutrinos?
  - Perhaps the neutrinos are decaying?
  - Need a mechanism for flavour change and a complete set of measurement for all flavours

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Bruno Pontecorvo

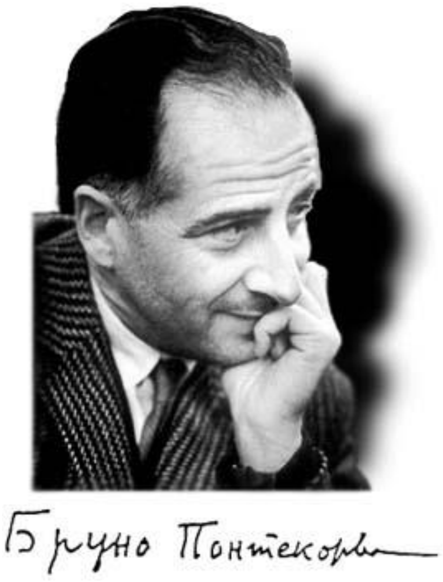
B. PONTECORVO

Joint Institute for Nuclear Research

Submitted to JETP editor October 19, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 247-249 (January, 1958)

RECENTLY the question was discussed[1] whether there exist other "mixed" neutral particles beside the K^0 mesons,[2] i.e., particles that differ from the corresponding antiparticles, with the transitions between particle and antiparticle states not being strictly forbidden. It was noted that the neutrino might be such a mixed particle, and consequently there exists the possibility of real neutrino $\rightleftarrows$ antineutrino transitions in vacuum, provided that lepton (neutrino) charge[3] is not conserved. In the present note we make a more detailed study of this possibility, in which interest has been renewed owing to recent experiments dealing with inverse beta processes.



- Concept of flavour not known at the time
- Pontecorvo hypothesized that the neutrinos oscillated between particle and anti-particle states.

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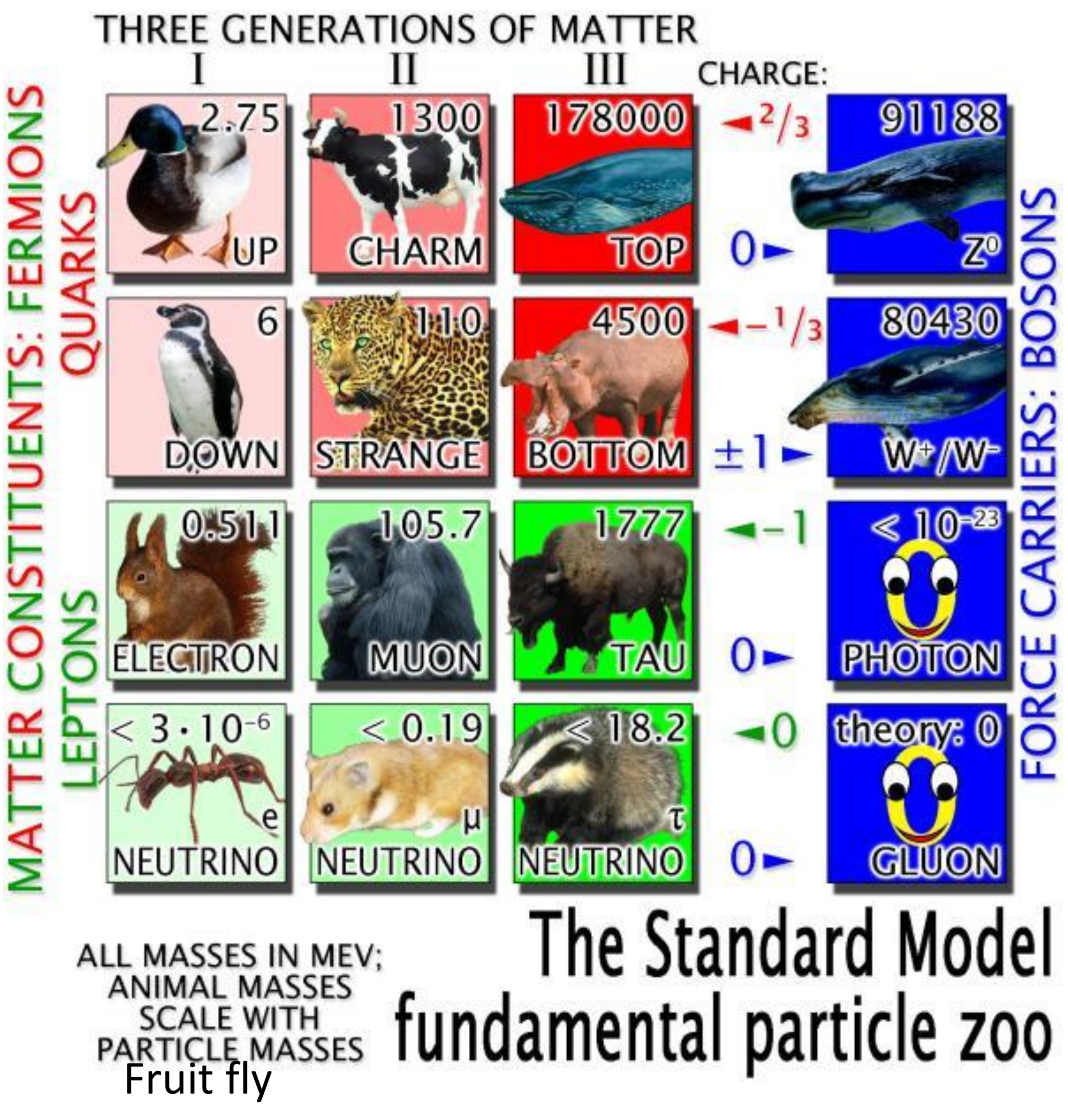
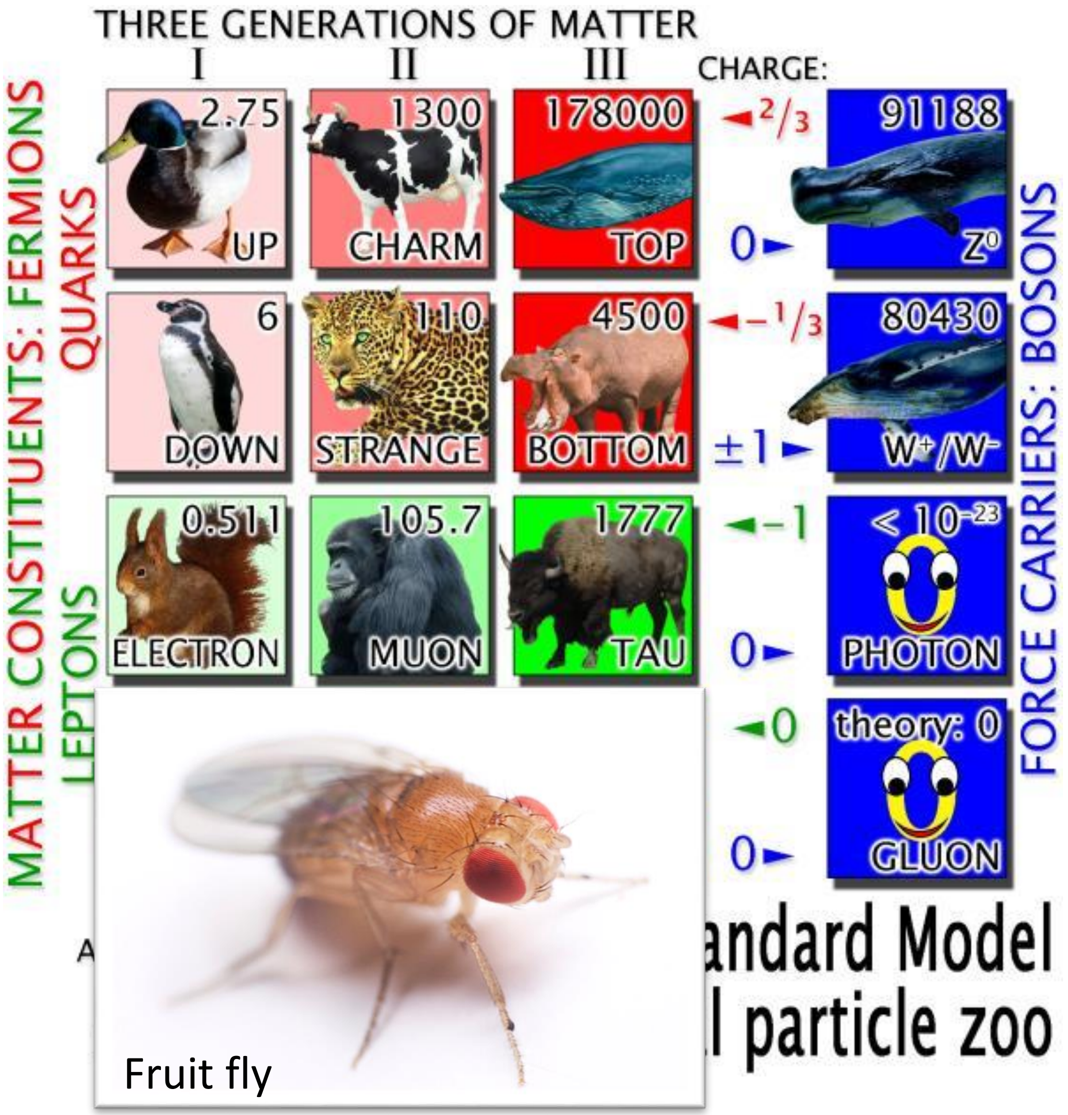
Neutrinos – flavour and mass



- Neutrinos are special:
  - their masses are much smaller than all other particle masses
  - but they are not zero (as we believed for a long time)
- Neutrino masses are not (directly) created by the Higgs boson – something different going on.
- Their small masses make them truly quantum mechanical objects.

Neutrinos and mass



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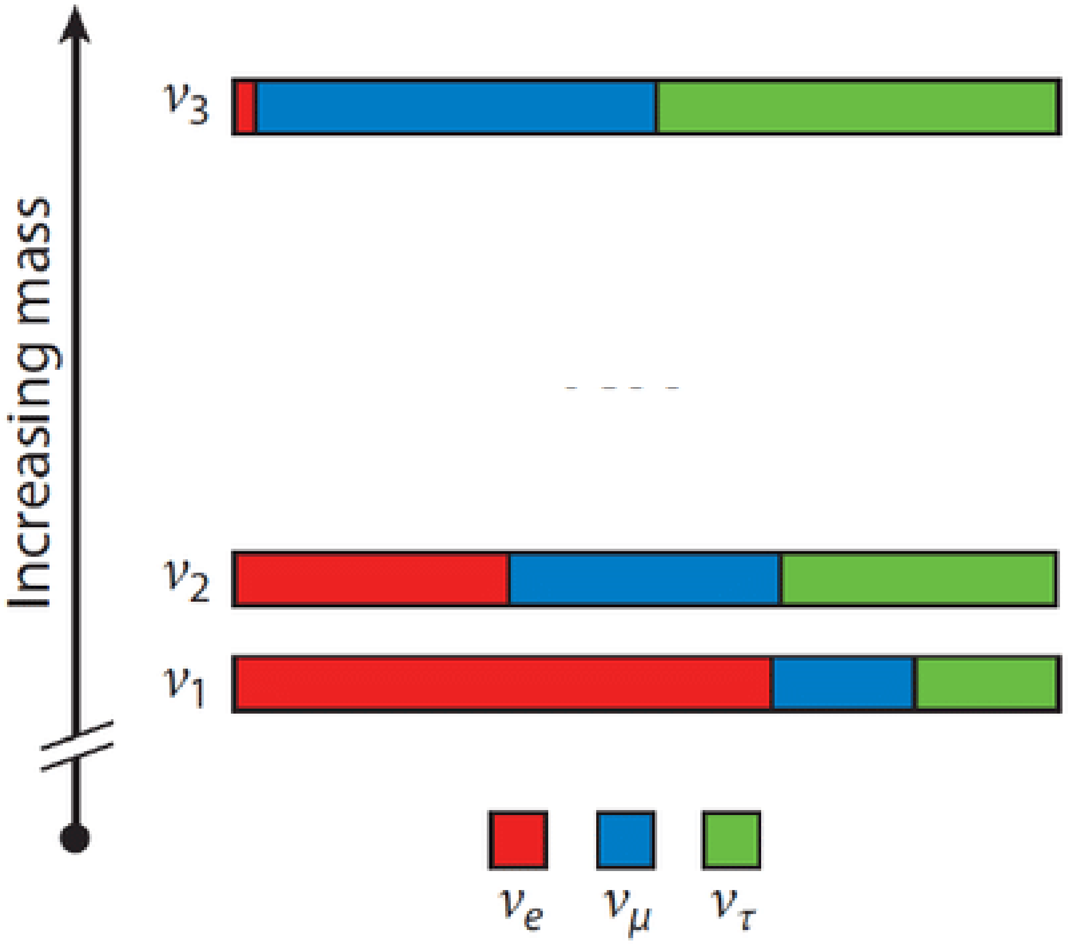
Mass and Flavour



- The neutrino "particles" with *masses* are not the same as the *"flavour"* neutrinos.
- Each neutrino particle (labelled 1,2,3) is made up of a different combination of flavour.
- Property depends on type of measurement.

Neutrinos are truly quantum

- An electron-neutrino emitted by the Sun is a combination of three different masses.
- The corresponding waves travel with different speeds.
- The waves oscillate at different frequencies and therefore interfere.
- The flavours of the neutrino thus change back and forth as the waves interfere constructively and destructively.

Credit: D. Schmidt, P. Vahle

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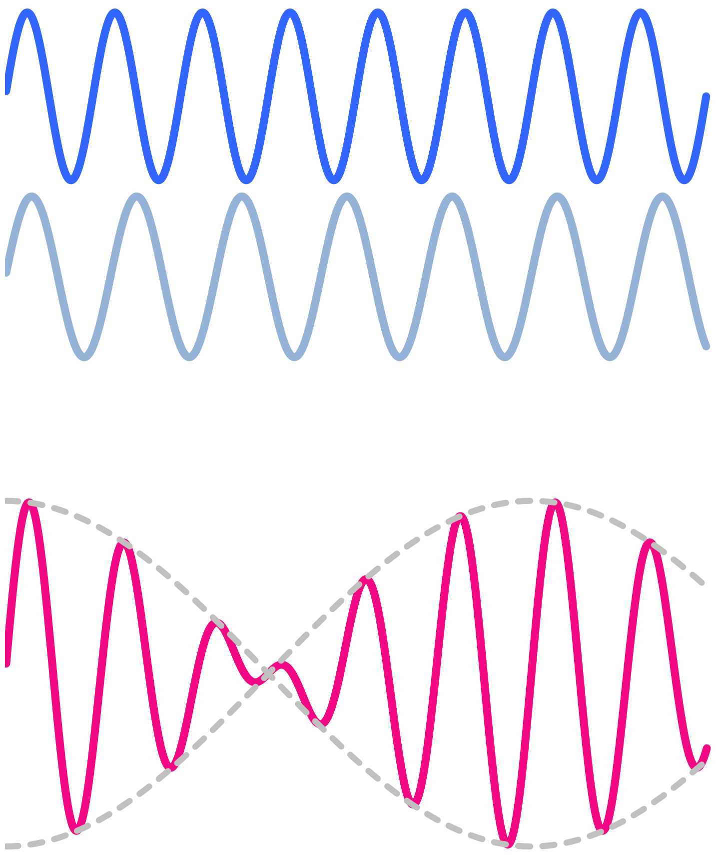

Credit: D. Schmidt, P. Vahle

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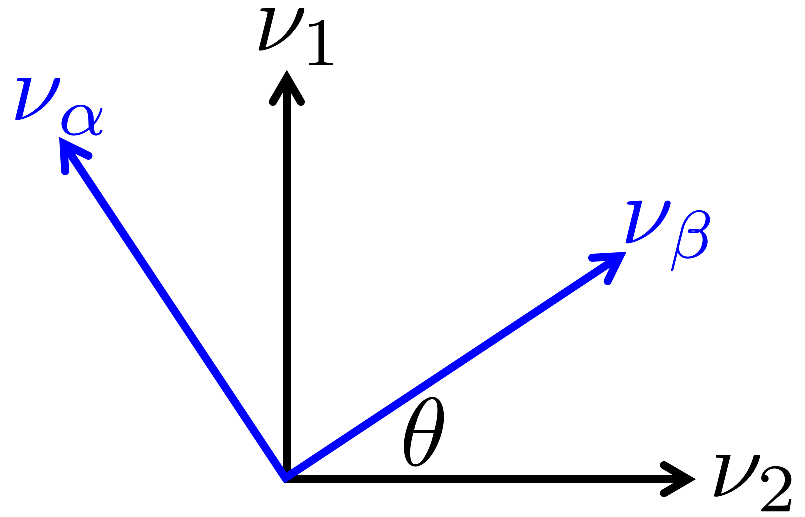
"If you think you understand quantum mechanics, you don't understand quantum mechanics."

Attributed to Richard Feynman

Two-flavour oscillations

Flavour states	"Rotation Matrix"	Mass states

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

Two-flavour oscillations

$$|\nu(t)\rangle = e^{i(E_1 t - pL)} \cos(\theta)|\nu_1\rangle + e^{i(E_2 t - pL)} \sin(\theta)|\nu_2\rangle$$

plane wave

$$\langle\nu_\beta|\nu(t)\rangle = \sin(\theta)\cos(\theta)(e^{i(E_2 t - pL)} - e^{i(E_1 t - pL)})$$

Two-flavour oscillations

$$|\nu(t)\rangle = e^{i(E_1 t - pL)}\cos(\theta)|\nu_1\rangle + e^{i(E_2 t - pL)}\sin(\theta)|\nu_2\rangle$$

plane wave

$$\langle\nu_\beta|\nu(t)\rangle = \sin(\theta)\cos(\theta)(e^{i(E_2 t - pL)} - e^{i(E_1 t - pL)})$$

$$E \approx p + \frac{m_i^2}{2E} \quad \text{and} \quad t = \frac{L}{c}$$

ultra-relativistic

Two-flavour oscillations

$$|\nu(t)\rangle = e^{i(E_1 t - pL)}\cos(\theta)|\nu_1\rangle + e^{i(E_2 t - pL)}\sin(\theta)|\nu_2\rangle$$

plane wave

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$$E \approx p + \frac{m_i^2}{2E} \quad \text{and} \quad t = \frac{L}{c}$$

ultra-relativistic

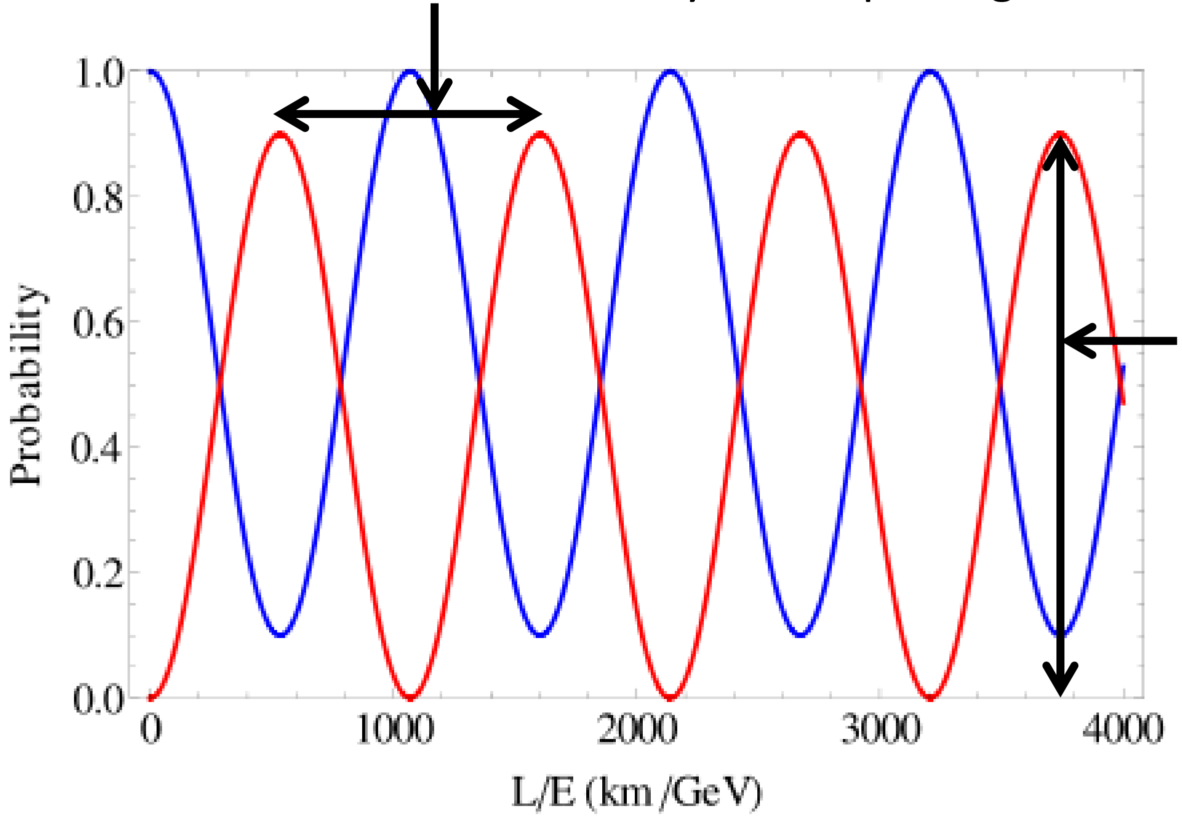
$$\langle\nu_\beta|\nu(t)\rangle = \sin(\theta)\cos(\theta)(e^{i\frac{m_2^2 L}{2E}} - e^{i\frac{m_1^2 L}{2E}}) = \sin(\theta)\cos(\theta)e^{i\frac{\Delta m_i^2 L}{2E}}$$

$$P(\nu_\alpha \to \nu_\beta) = \langle\nu_\beta|\nu(t)\rangle^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta m_i^2 L}{2E}\right)$$

Two-flavour oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2_{21}[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

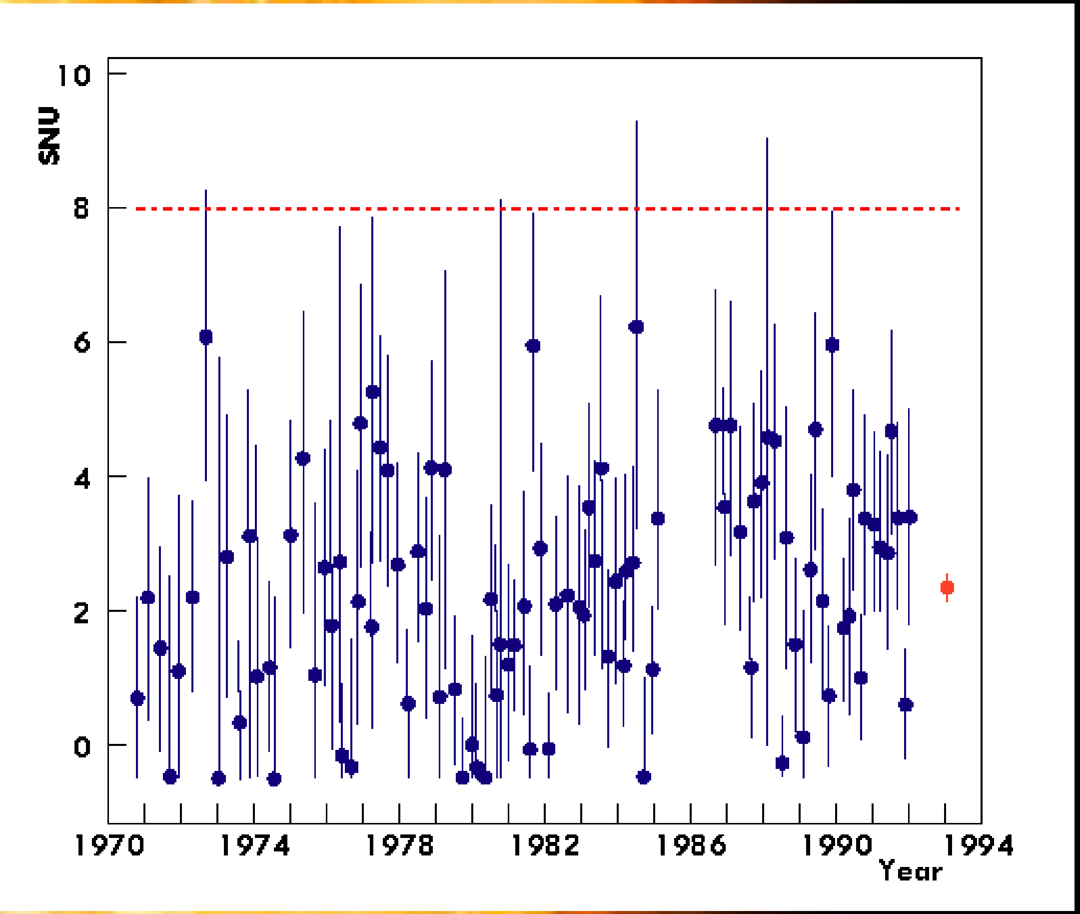
Rate driven by mass splitting Δm^2



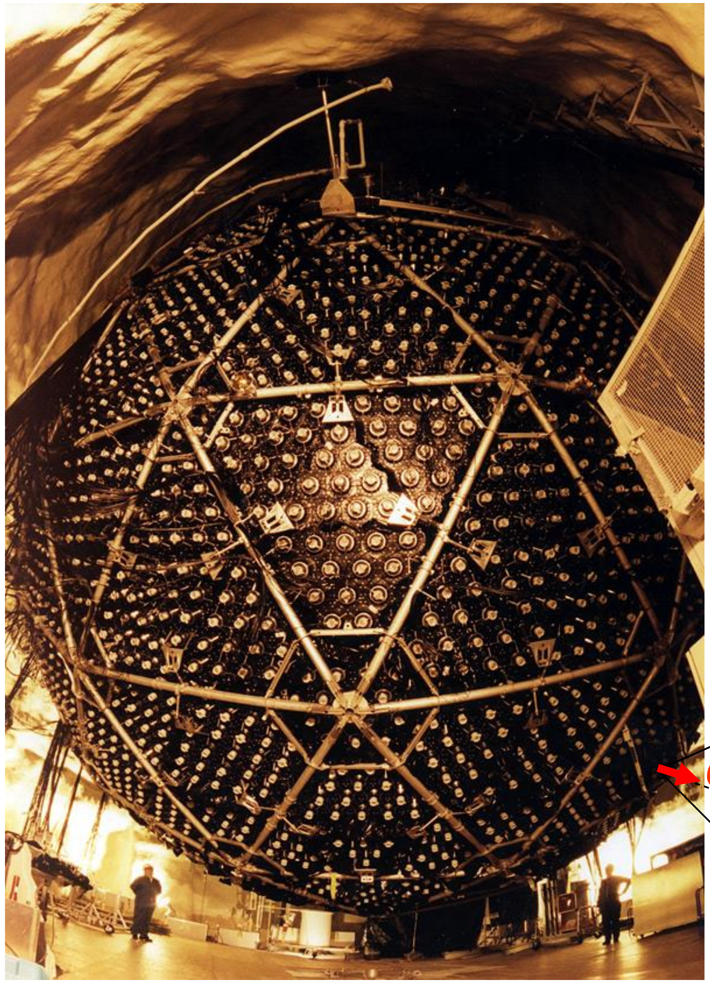
ν_α component

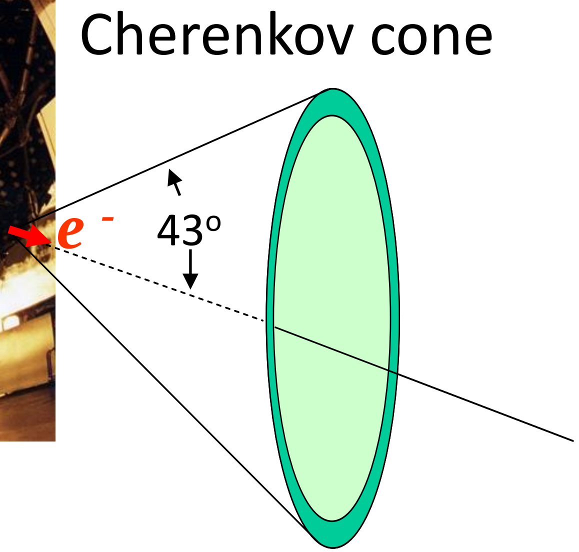
ν_β component

Amplitude driven by mixing angle $\sin^2(2\theta)$


SNU
10
8
6
4
2
0
1970
1974
1978
1982
1986
1990
1994
Year

SNO Detector



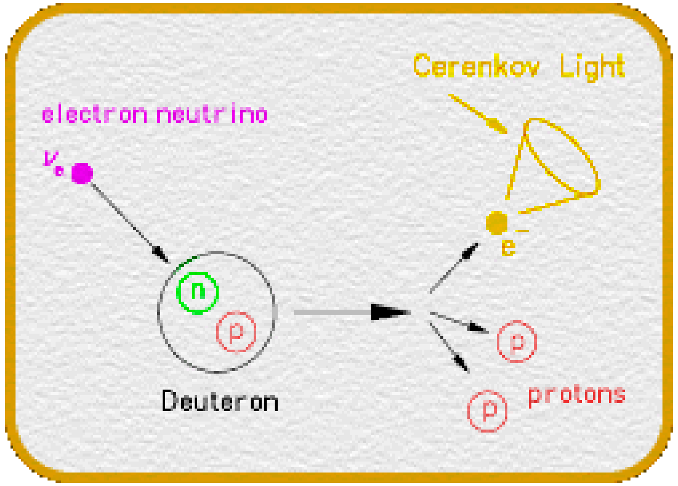


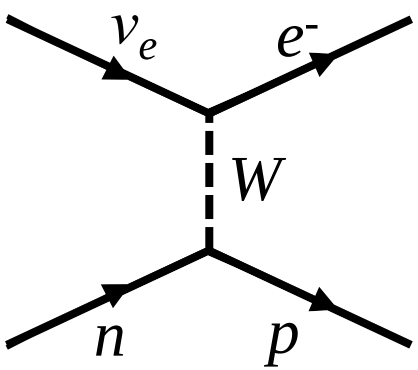
- Davis experiment only showed that some of the electron-neutrinos went missing.

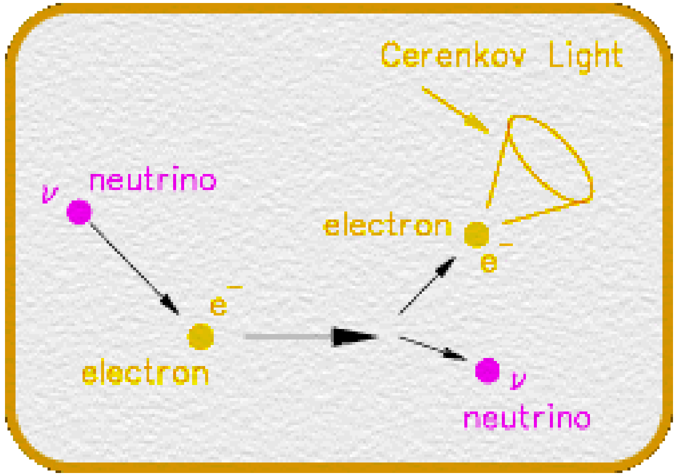
- Need a detector that can measure different neutrino flavours to confirm the 3-flavour oscillation model.

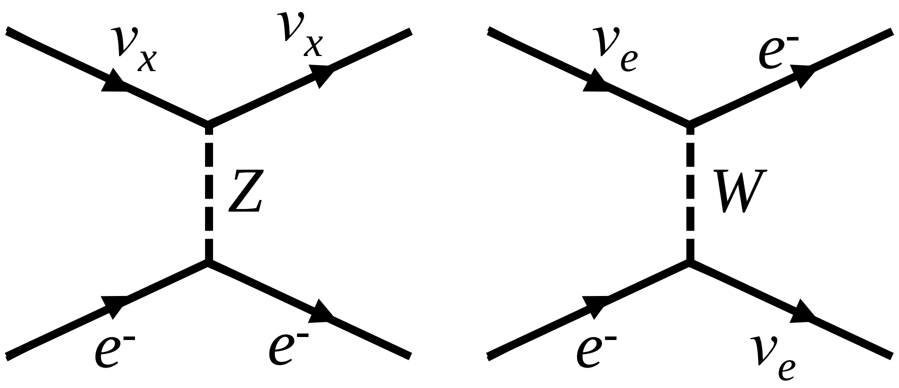
- SNO detector – filled with heavy water - is sensitive to Cherenkov light from scattered electrons and from photons produced when neutrons are captured.

Neutrino interactions in SNO





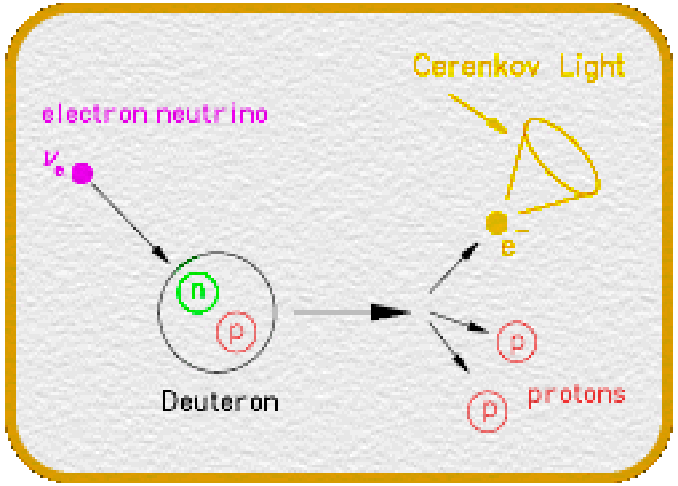


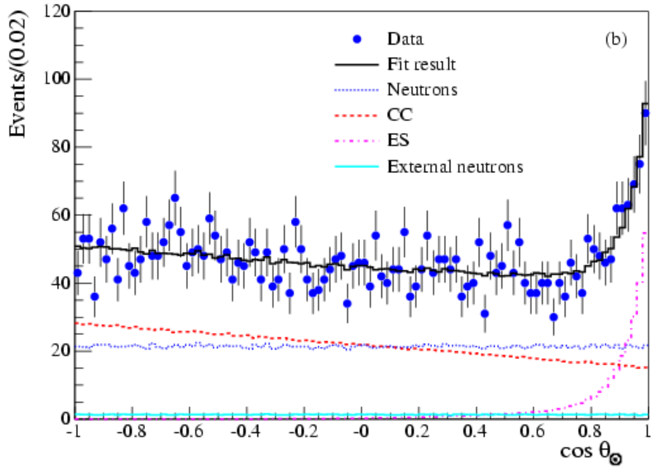


Charged current interaction:
Sensitive only to ν_e

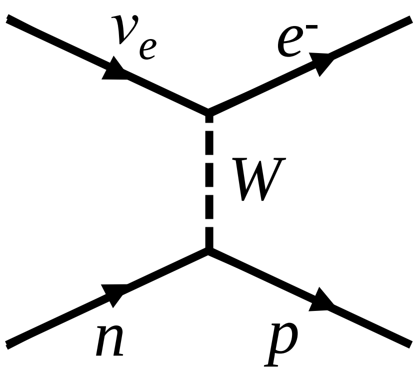
Elastic scattering:
Sensitive to charged and neutral current.
ν_e dominate by a factor of 6

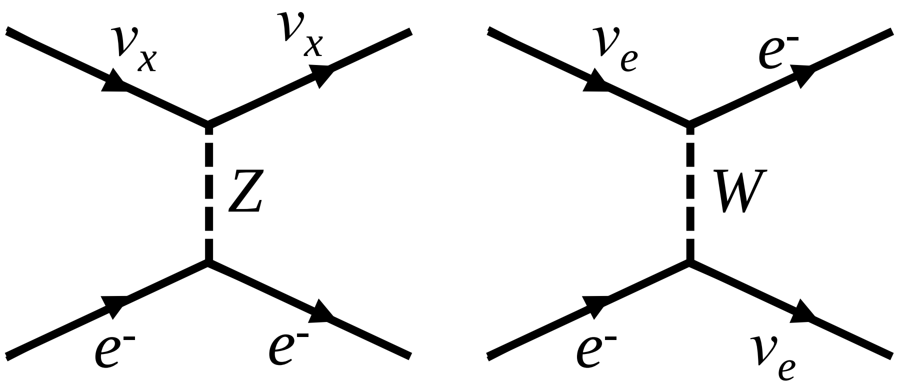
Neutrino interactions in SNO





Sensitive to neutrino direction





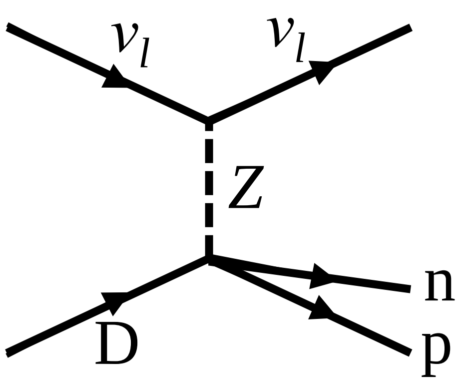
Charged Current interaction (CC):
Sensitive only to ν_e

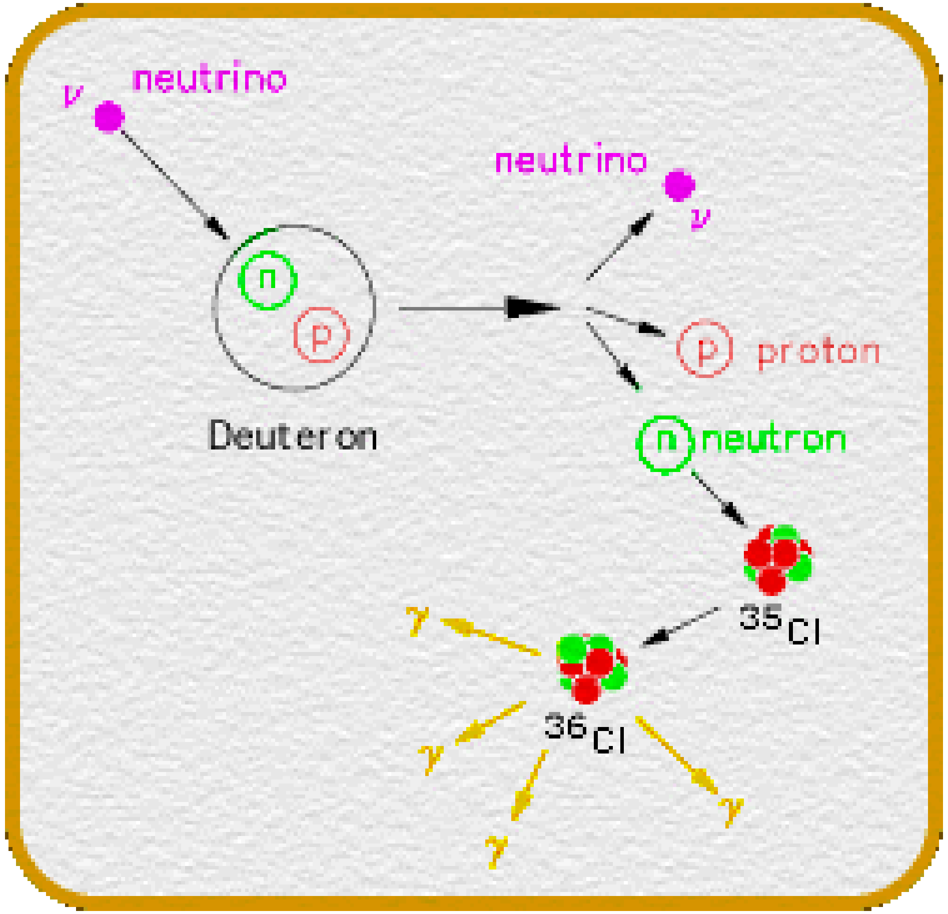
Elastic Scattering (ES):
Sensitive to charged and neutral current.
ν_e dominate by a factor of 6

MANCHESTER 1824

The salt phase

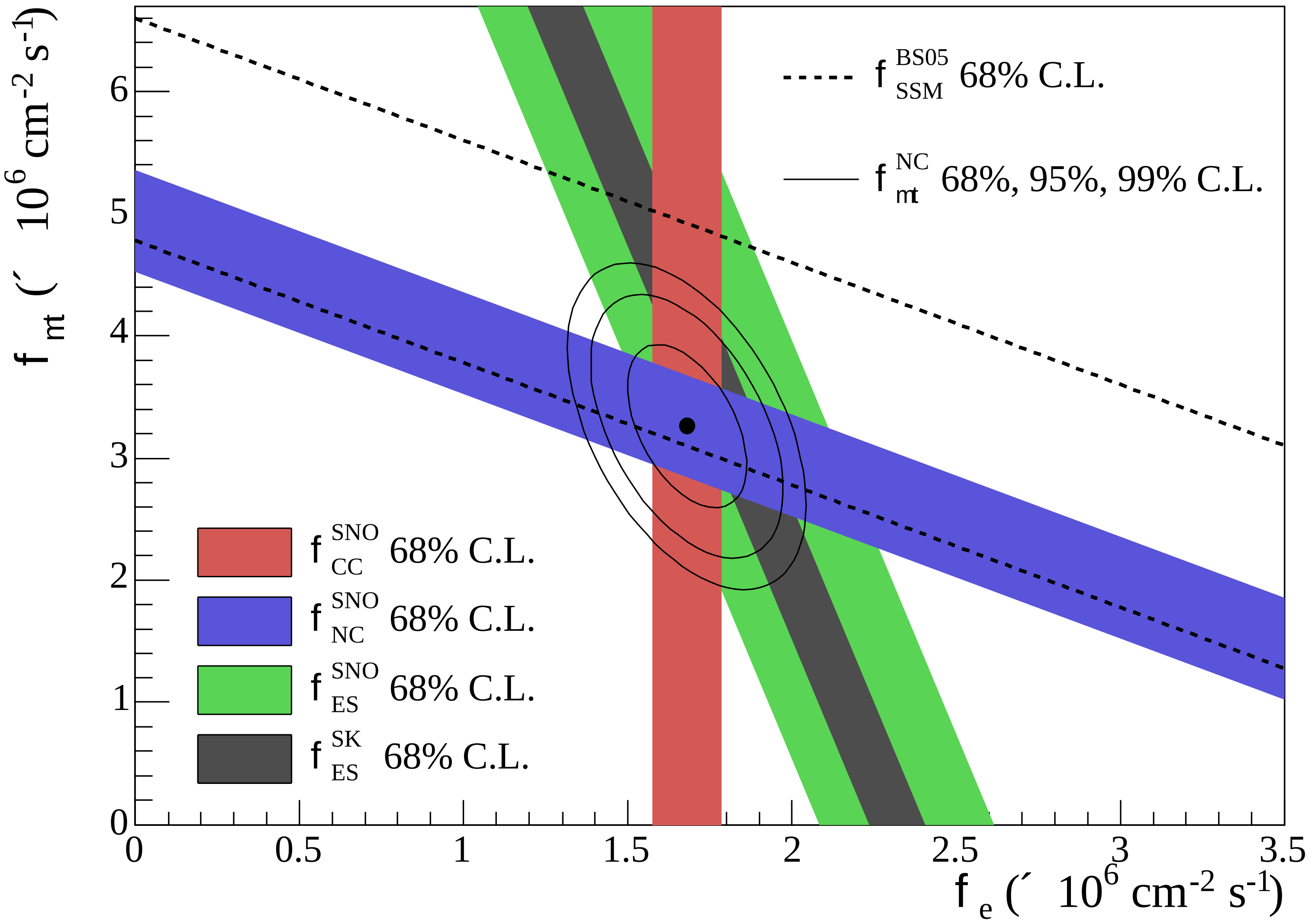
- In its second phase, SNO was filled with two tons of NaCl
- ^{35}Cl has a high neutron absorption cross, releases γ of up to 8.6 MeV
- Neutral current interaction equally sensitive to all three neutrino flavours





MANCHESTER 1824

SNO demonstrates flavour change



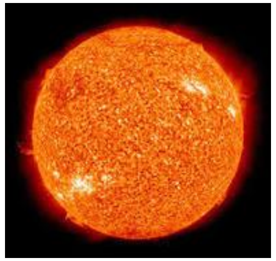
PMNS Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

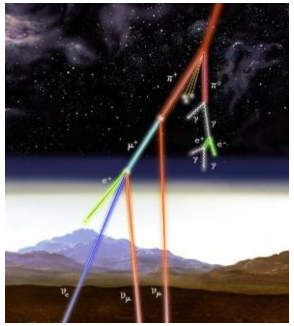
Pontecorvo–Maki–Nakagawa–Sakata

$$c_{ij} = \cos\theta_{ij};\, s_{ij} = \sin\theta_{ij}$$

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$



θ_{13}: mixes ν_e with ν_3
δ: complex phase

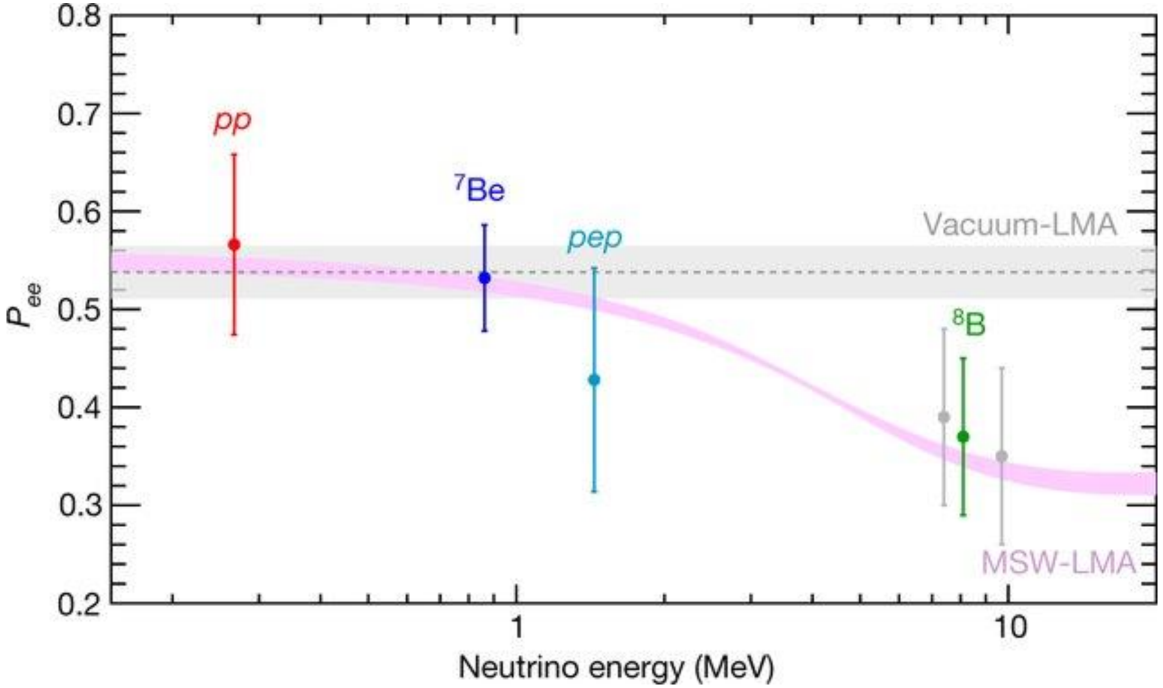


- θ_{12}: “solar mixing angle”
- mixes ν_e with ν_1 and ν_2

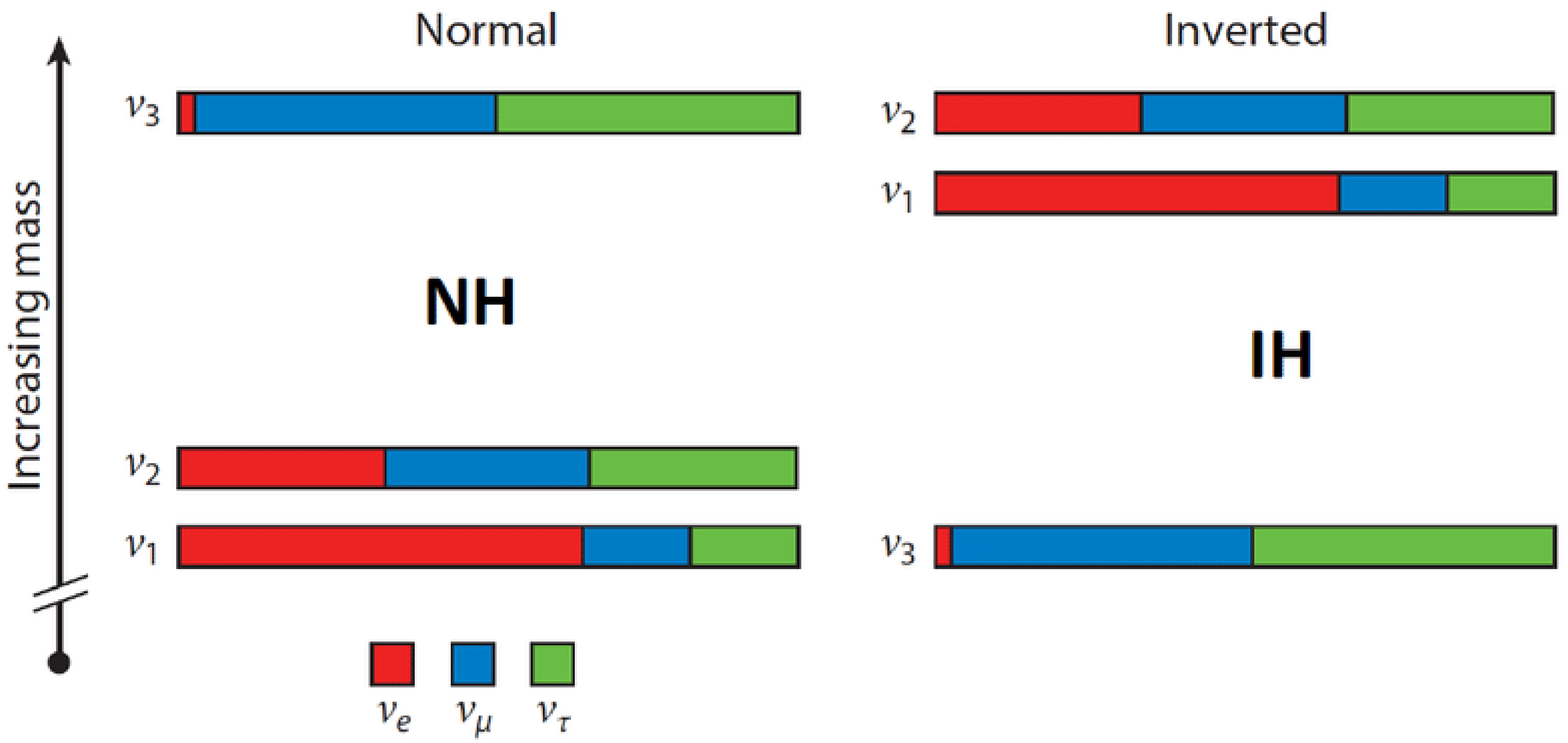
- θ_{23}: “atmospheric mixing angle”
- mixes ν_μ with ν_τ

The MSW Effect

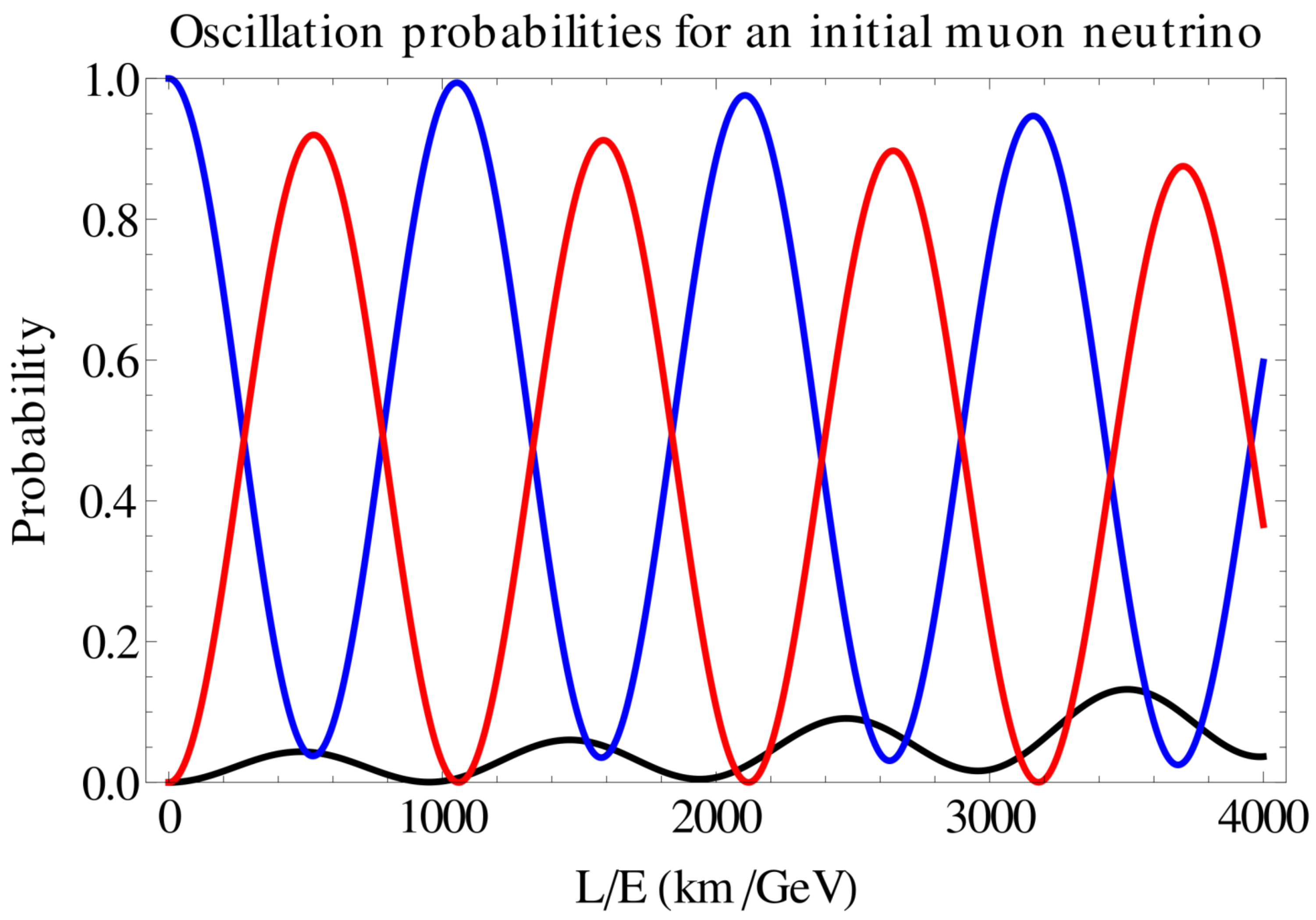
- When neutrinos travel over long distances through dense matter (Sun, Earth), their propagation is modified through coherent forward scattering off particles (electrons)
- This effect modifies the flavour oscillation probability (Mikhaev, Smirnov, Wolfenstein)
- MSW effect can be enhanced through a resonance condition
- Neutrino and anti-neutrino oscillation probabilities affected differently (not related to CPV)
- MSW effect depends on the sign of Δm^2



Solar mixing fixes sign of Δm_{21}

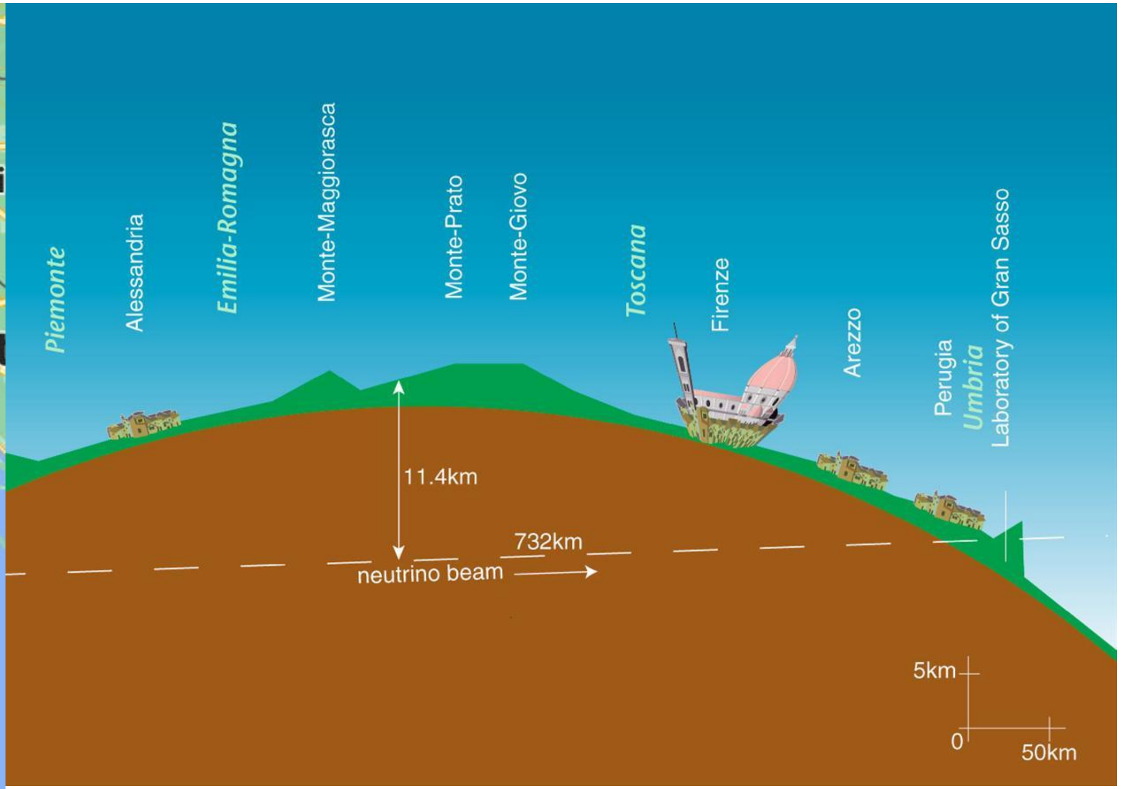


Where are the tau neutrinos?



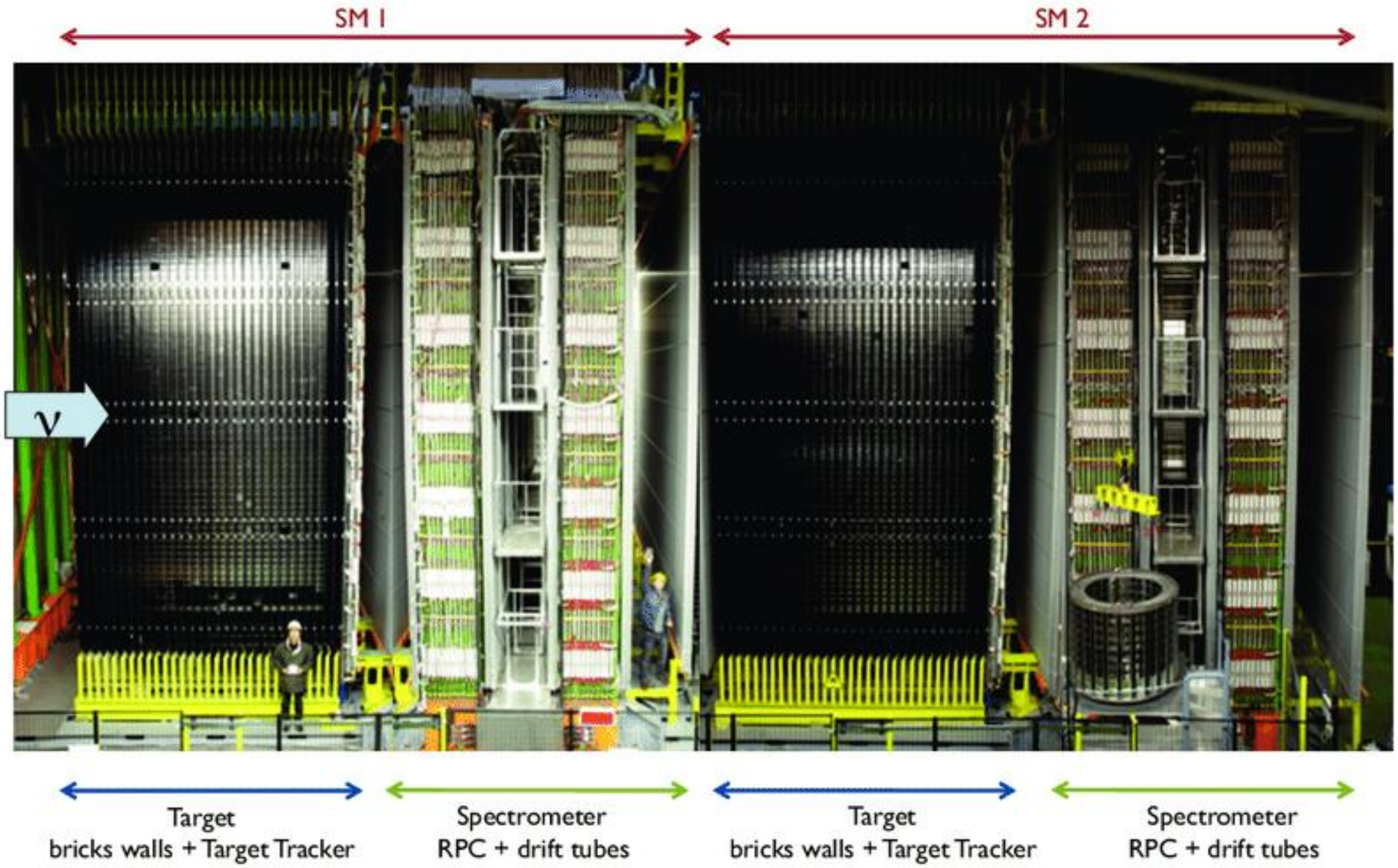
Baseline/Neutrino energy

CNGS ν_μ beam from CERN to Gran Sasso



L/E ≈ 732 km/17 GeV = 43

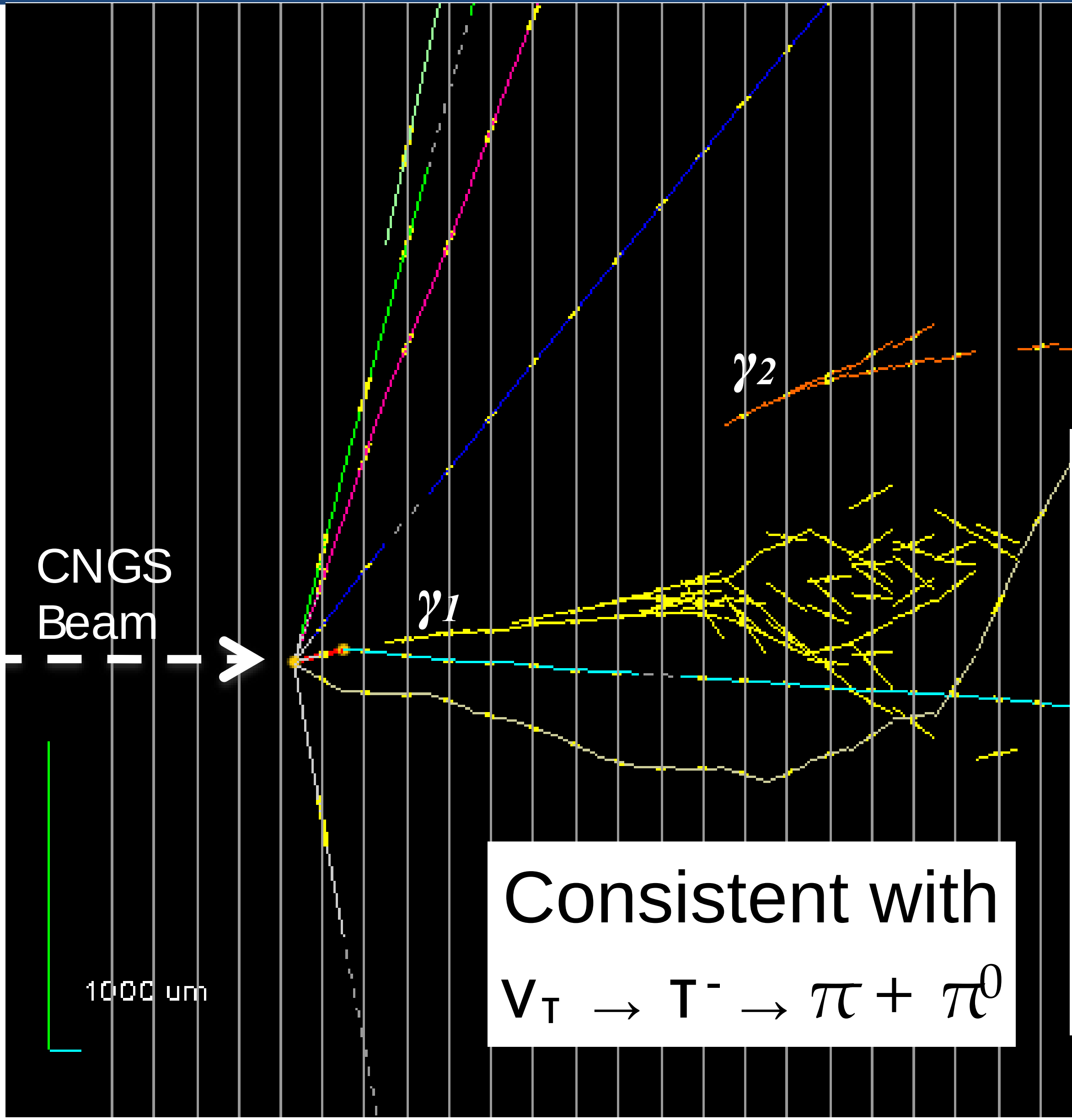
OPERA experiment at Gran Sasso



Target Tracker:

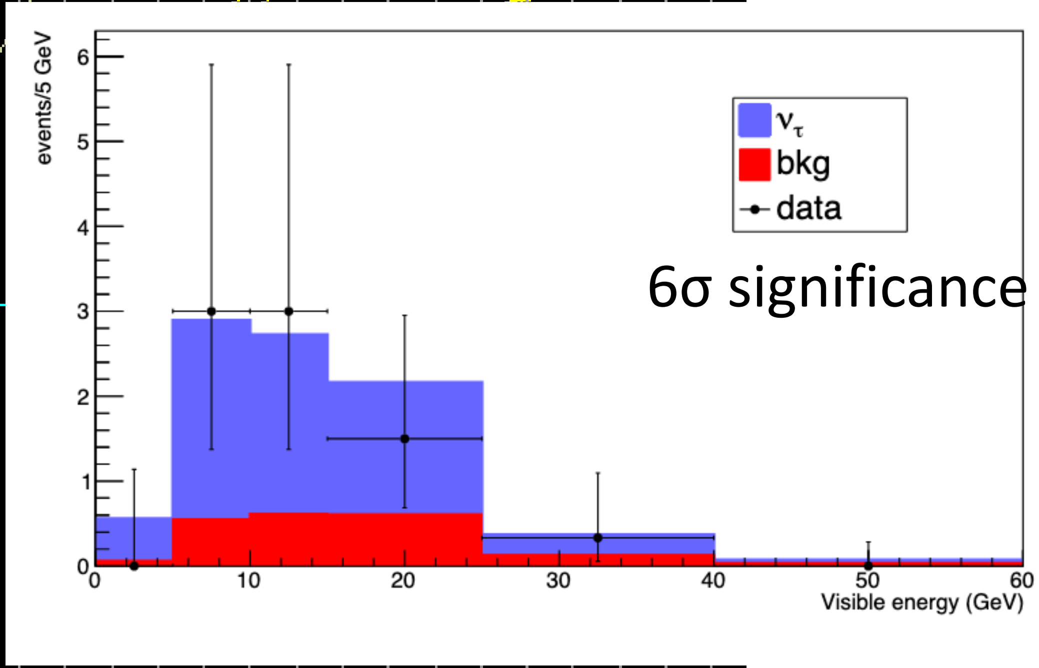
75,000 emulsion/lead modules or ”bricks”

First observation of $\nu_\tau \rightarrow \nu_\tau$ appearance



Consistent with

$\nu_\tau \rightarrow \tau^- \rightarrow \pi + \pi^0$



6σ significance